DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 108

GROUND CONNECTIONS FOR ELECTRICAL SYSTEMS

BY

O. S. PETERS, Assistant Physicist
Bureau of Standards

ISSUED JUNE 20, 1918

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CONTENTS

I. INTRODUCTION

Ground connections have come in recent years to play an increasingly important part in electrical systems of almost every kind. One of their chief functions is that of protecting persons against electrical dangers. Where depended upon for this purpose, they should be carefully made, because if they are poorly made, or inadequate for the purpose for which they are intended, loss of life or serious personal injury may result. Nevertheless, surprisingly little has been done to make generally known the

information available concerning ground connections in common use, and research on the subject has been limited. It is true, of course, that the desirability of grounding has been extensively discussed in its different phases; and although there still is some discussion as to the extent to which grounding should be carried, there is now fair agreement as to the parts of electrical systems which can be operated most advantageously when connected to earth.

With regard to the performance of ground connections under operating conditions, and the physical characteristics which they must possess to meet the requirements placed upon them, comparatively little has been written. As a result, information which is important to persons directly engaged in the safeguarding of life and property from electrical dangers by the use of ground connections is not readily obtainable. The consequences of this difficulty in obtaining information are evident in a more or less general lack of thoroughness and uniformity in the practice of grounding, and accidents due to inadequate ground connections not infrequently occur.

The object of this paper is to present the information now available concerning ground connections and their uses, and to supplement this information with new experimental evidence which, among other things, shows the necessity for basing specifications for ground connections upon their physical characteristics rather than upon arbitrary methods of construction as has been the custom to a large extent in the past. Considerable space is devoted to discussing the manner in which danger arises from ungrounded electrical systems, and also the desirability of grounding to avert such danger. The subject is taken up with special reference to the grounding rules of the National Electrical Safety Code[1] under the following main topics: (1) Resistance of ground connections; (2) their uses and service conditions; (3) different forms of ground connections and the electrical characteristics of each; (4) mechanical construction; (5) inspection and testing; (6) fire hazard and interference with service; (7) costs; (8) bases for specifications; and (9) field measurements of the resistance of ground connections.

With the object outlined above in view, a careful survey of the literature on grounding and ground connections has been made; considerable experimental work has been done in the laboratory and in the field, and correspondence and conferences had with

[1] See Appendix II.

representatives of corporations engaged in the generation and distribution of electrical energy. The results of this study will be taken up after referring to some of the terms used in the following discussion, and also stating briefly the purpose of a ground connection.

1. TERMINOLOGY

The terms "ground," "permanent ground," "ground connection," and, in a few cases, "earth connection," as herein used, refer to electrical connections intentionally made between electrical circuits, or conducting bodies in close proximity to electrical circuits, and metallic bodies embedded in the earth, such as water pipes, plates, or driven pipes.

Every connection between electrical circuits and ground or near-by conducting bodies made, not by design, but by accident, as by the breaking of wires or failure of insulation, is referred to as an "accidental ground."

2. PURPOSE OF GROUND CONNECTIONS

The purpose of a ground connection is to keep some point in an electrical circuit, or some conducting body, at, or as near as practicable to, the potential of the ground in order either that safety to life and property be secured, or that there be increased convenience and continuity of service in the operation of electrical systems. "Ground" here may mean either the soil itself, or conducting bodies in contact with it or extending into it. Examples of the latter are steel building frames, steel poles, and water and gas pipes, and fixtures in buildings. In many instances it is necessary that there be a considerable flow of current through the ground connection in order to prevent the potential of an electrical circuit or a conducting body from rising to a dangerously high value above that of the ground. The soil offers more or less resistance to this current flow, and this resistance determines in large measure the effectiveness of the ground in protecting against high voltage. The nature of the resistance of a ground connection will therefore first be considered.

II. RESISTANCE OF GROUND CONNECTIONS

If two electrodes, such as pieces of iron pipe several feet in length or plates or other bodies of metal, are embedded in earth at a distance from each other and have impressed upon them a steady alternating difference of potential, a current will flow between

them, the value of which depends upon the electrical resistance offered by the soil. This resistance is made evident by the liberation of heat when current is flowing, and because of its effects on the performance of ground connections in service, it is of interest to consider the factors which affect it and its distribution in the region surrounding the metallic bodies.

1. CONTACT RESISTANCE BETWEEN METAL AND EARTH

One factor which has in many instances been considered as contributing to the resistance of a ground connection is that of contact resistance between metal and earth. In order to obtain an idea of the magnitude of this contact resistance, some measurements were made at the Bureau of Standards. For the purpose of these measurements, several samples of earth were used, each of which was thoroughly mixed before testing in order to make the resistivity as uniform as possible throughout. Tests were then made by placing different quantities of each sample in a cylindrical vessel having an iron bottom and glass-lined sides, compressing it by forcing an iron piston down upon it, and measuring the electrical resistance between the piston and the metallic bottom, using alternating current at 60 cycles per second. Measurements made at the same unit pressure, and with the cylinder filled to depths ranging from 2 to 9 cm., showed the same specific resistance for each depth; that is, within the limits of accuracy of the measurements, or about 2 per cent. If contact resistance were present, an apparently greater specific resistance would have been shown with the smaller depths of earth in the cylinder than with the greater depths, but this was found not to be the case; consequently, it may be concluded that the effects of contact resistance between clean iron and earth when firmly pressed together are negligible, at least as far as practical purposes are concerned. The contact resistance between earth and metals other than iron has not been determined, but it seems reasonable to infer that for those metals commonly used for ground connections, viz, copper and galvanized iron, the latter of which presents a zinc-coated surface, the same results would be obtained.

In practice, however, clean metal is not always found. The electrodes used in making ground connections may be covered with substances such as rust, paint, or grease, and these in some instances are not unlikely to form a more or less insulating layer between metal and soil. Rust, of course, is the one most commonly

found, but in none of the experiments thus far conducted by this Bureau upon the corrosion of iron in soil has it developed that a layer of rust appreciably increases the resistance to flow of current away from the metal. From the results of these tests, and also from the fact that rust layers formed in soil are permeable to soil water and consist of particles of iron oxide of no greater insulating qualities than the particles forming the soil itself, it may be safely stated that rust is of no effect in increasing the resistance of a ground connection. Paint or grease, however, should be removed before the metal is buried.

A case in which an apparent contact resistance between metal and earth may arise is where a ground connection is required to carry direct current. This may be important, especially in making resistance measurements at low voltage, and the effects of direct current, as compared with these of alternating current, should be given careful consideration. For when direct current is used in making resistance measurements, electrolysis takes place at the surface of the electrode. By this means gas is liberated which soon forms a high-resistance layer between metal and earth, and in conjunction with other factors, makes a very marked difference (generally an increase) in the apparent resistance as compared with the resistance obtained with alternating current. The magnitude of this difference in resistance depends upon the polarity of the electrode, upon the rate of current flow, upon the rate at which gas is able to diffuse from the surface, and also upon the counter electromotive force of polarization. It may amount to as much as 20 or 25 per cent.

On the other hand, when alternating current is used, the resultant electrolysis is very small. The rate at which reversals of current would have to take place in order entirely to prevent electrolysis under all conditions has not been determined, but some experiments have been conducted recently at the Bureau of Standards which indicate the magnitude of the resultant electrolysis with current at 60 cycles, or 120 reversals per second. These experiments were made on iron and lead in moist clay. It was found from tests lasting through several weeks that the amount of iron or lead lost with a certain number of ampere-hours of alternating current was a fraction of 1 per cent of the loss with an equal number of ampere-hours of direct current.[2] There are, of course, other products of electrolysis than dissolved

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[2] Technologic Paper No. 72 of the Bureau of Standards.

metal which would affect measurements of the resistance of ground connections, but it seems that it may safely be inferred from the results just mentioned that they are comparable in amount with the dissolved metal and are, therefore, of negligible effect as far as measurements in practice are concerned.

From the foregoing discussion, it appears, then, that if contact resistance is present in a ground connection, it is something which is not inherent in the contact between clean metal and packed earth, or even between rusty metal and packed earth. As indicated above, it is most likely to be due to an impervious nonconducting coating on the surface of the metal, such as paint, grease, or gas formed by chemical action or electrolysis. Furthermore, in the measurement of resistance of ground connections with direct current, the contact conditions between metal and soil are disturbed to an appreciable extent by the action of the current, whereas with alternating current at 60 cycles per second, this disturbance is inappreciable. Alternating current is, therefore, preferable for making measurements of the resistance of ground connections.

2. TOTAL RESISTANCE OF A GROUND CONNECTION

Having considered the matter of contact resistance between metal and earth, attention may now be turned toward what may be called the actual or total resistance of a ground connection. This must be considered in every case. It consists of three parts, viz, (1) a part contributed by the ground wire or other conductor, which serves to make an electrical connection between the buried electrode and the electric circuit or metallic body which the ground connection is designed to serve; (2) a part contributed by the buried electrode itself; (3) a part contributed by the soil. The part contributed by the ground conductor may properly be taken as a part of the total resistance because, as far as the effect on the electric circuit or metallic body mentioned above is concerned, it makes no difference whether the resistance is in the conductor or the soil. Its importance is not great, however, unless an exceedingly long ground wire is used, or connection is made to a long service pipe in making water-pipe grounds.

The resistance of the buried electrode enters because of the fact that the current flows into the electrode at a point, that is, where the ground conductor is attached, and to reach the surface must pass through the metal. Each element of current, there-

fore, traverses a path of greater or less length depending upon the distance between the point where the ground conductor is attached and the point where the particular element of current passes into the soil. The part of the total resistance contributed by the buried metal is the combined resistance of all these paths in parallel. The resistivity of metals, however, is exceedingly small in comparison with that of soils, which has been found by measurement to range from a few hundreds to many thousands of ohms[3] for a centimeter cube.[3] Hence, for electrodes of limited extent, the part of the total resistance contributed by the metal can be neglected and consideration confined to that due to the soil surrounding it. For electrodes of great length and comparatively small cross section, however, this may not be the case. Where water pipes are used, for instance, a large part of the elements of current must traverse the pipe over considerable distances before passing into the ground, and since these paths are of great length in comparison with their cross section, they may contribute very appreciably to the total resistance, especially if the pipe contains high-resistance joints. Lead joints, under ordinary circumstances, of course, are of such low resistance that their effects are of little consequence, but cement or "leadite" joints are of high resistance, and where these are used they may so contribute to the total resistance of a water-pipe ground connection as seriously to impair its effectiveness. The resistance of water-pipe grounds is considered again in Section IV, 5 (*a*).

The part of the total resistance contributed by the soil is the most important in nearly all cases. When current flows away from the electrode, each element of current traverses a path of variable cross section to its destination, which in practice is always another electrode at some distance away. The resistance offered by the soil, then, is the combined resistance of all the paths of the current elements in parallel, and since the resistivity of soil, as already pointed out, is high, this resistance will be high unless the electrode is very large and the comparative number of paths, therefore, very great. It should be mentioned that where current flows from one electrode to another, the resistance, as just set forth, is due to the soil surrounding two electrodes which may be said to be in series. To obtain the resistance to flow of current away from a single electrode, current may be made to flow from it to an electrode of such great extent that its resistance could be

[3] Technologic Paper No. 26 of the Bureau of Standards.

considered negligible. If two electrodes are placed at a distance from each other equal to several times their greatest dimension, the resistance to flow of current from one to the other is practically the sum of the resistances of each of the two grounds, a fact which is very useful in making resistance measurements. It is of interest to point out briefly the manner in which the resistance of the soil is distributed, especially about buried electrodes of limited extent.

3. DISTRIBUTION OF RESISTANCE IN THE EARTH ABOUT A METALLIC BODY

As a concrete example it is convenient to take a hemispherical electrode which may be supposed to be embedded in earth of uniform resistivity with its convex surface down and its plane surface flush with the surface of the ground. If very thin shells of uniform thickness are marked off concentrically with such a hemisphere, their mean areas will vary directly as the squares of their radii, and hence their resistances will vary inversely as the squares of their radii. Any part of the total resistance to flow of current away from such an electrode can be exactly stated by taking the sum of the resistances of the shells from the surface of the hemisphere to the desired distance. This inverse-square law, which holds exactly for a hemispherically shaped electrode, may also be considered as a rough approximation to the conditions as to distribution of resistance about any small electrode, such as a driven pipe; that is, a large part of the total resistance is found near by. It should be added that if the soil, instead of being of uniform resistivity as assumed above were variable, the foregoing simple case would not hold; the distribution of resistance would be more complex. An example is given later in which a quantity of salt is placed around a driven pipe in order to reduce the resistivity of the adjacent soil.

The practical importance of the character of the distribution of resistance about an electrode buried in the earth appears in its effect on the potential gradient in the vicinity of the electrode when heavy current is passing from it. Actual measurements, the results of which will be given later in this paper, show that in the case of driven pipes about 90 per cent of the total resistance is generally encountered in the first 6 to 10 feet; hence, the potential gradients on the earth's surface near the pipe may be high enough in the event of heavy current flow to cause a drop of potential between the pipe and points within reaching distance of it great enough to be dangerous to human life. This matter is discussed in detail in Section IV, 10.

4. FORMULA FOR THE RESISTANCE OF A GROUND CONNECTION

The simple physical idea of the distribution and value of the resistance of a ground connection which has just been given, serves very well for the purpose of illustration. But for working up certain kinds of experimental data, and also for showing the most advantageous way in which to make ground connections, it is desirable to go a step further and express the value of the resistance in terms of the resistivity of the soil and the dimensions and position of the metallic body. A mathematical formula which fulfills these conditions is readily derived and is given in many textbooks on electricity and magnetism. Its common form is as follows: $R = \frac{\rho}{2\pi C}$, where R is the resistance to flow of current away from the electrode forming the ground connection; ρ, the resistivity of the soil; and C, the combined electrostatic capacity in free space of the electrode and its image above the surface of the ground.[4] The value of C, it may be added, is a constant for any given shape and arrangement of an electrode.

From this formula, it appears that the resistance of a ground connection of any form can be calculated if the resistivity of the soil is known, but in practice difficulties are encountered which limit the use of the method very materially. The chief difficulty is that of obtaining convenient means for expressing the value of C, and this confines the use of the formula to a few simple cases. The resistivity of most soils is also far from uniform, and this presents another difficulty. The principal use of the formula in experimental work is that of drawing smooth curves from the results of observations on driven pipes, which, on account of the nature of the soil in most localities, are bound to be irregular. In this case the value of the electrostatic capacity of the pipe and its image in free space can be approximated by considering it an ellipsoid of revolution. Approximations which are very useful can also be made for other forms of electrodes such as long metal strips or wires.

In addition to serving to a certain extent as the basis of a method for working up observations, the formula given above also serves another purpose, which is, perhaps, still more important, and that is to show that the manner in which buried metal must be distributed in order to obtain the best results—that is, the

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[4] For a derivation of this formula and a short discussion of electrical images as applied to this case, see Appendix III.

least resistance for a given amount of material—is also the manner in which it must be distributed to give the greatest value of C. This is a fact which can not be too strongly emphasized, inasmuch as there are recommendations in existence concerning the installation of ground connections in which area of plate or other electrode seems to be considered the most important matter and no thought given to distribution of metal. If due regard is given to this, much better results can be obtained in many cases for a given amount of material and labor, than if it is neglected. As an illustration, there is the matter of laying a wire in a stream bed to form a ground connection. Instead of coiling the wire, it should be strung out to its greatest length, because in this position the value of C is greatest, and hence, the value of R is the least. The importance of having a low value for R appears from a consideration of the uses found for ground connections in practice and the conditions under which they must operate.

III. USES AND SERVICE CONDITIONS OF GROUND CONNECTIONS

There are great differences in the service conditions imposed upon ground connections in the different practical cases involving their uses, and for that reason it is desirable to consider each case separately. The most important kinds of electrical circuits and apparatus or machinery with which ground connections are used, are the following: (1) Low-voltage,[5] alternating-current circuits; (2) direct-current distribution systems; (3) detectors of accidental grounds; (4) frames of electrical machines; (5) metallic bodies near or inclosing electrical circuits; (6) high-voltage transmission and distribution systems; (7) electrical systems under construction or repair; (8) lightning arresters and overhead ground wires; (9) lightning rods; (10) meter circuits. Ground connections are also used in signaling circuits, and in a number of ways for testing purposes. In the following discussion special emphasis is given to cases involving life hazard, for here the conditions to be met by the ground connection are more rigorous than where simply property hazard or convenience of operation and continuity of service are concerned.

[5] The term "low voltage," as here used, refers to circuits of the voltages commonly used for distribution within buildings to electrical utilization installations, generally 750 volts or less, while "high voltage" refers to circuits of the voltages commonly used for transmission and distribution in overhead and underground lines, except those directly connected to electrical utilization installations, generally over 750 volts.

1. LOW-VOLTAGE, ALTERNATING-CURRENT CIRCUITS

Low-voltage, alternating-current circuits are grounded primarily for the purpose of averting a life hazard which is due to their proximity to high-voltage circuits in transformer windings, on pole lines, in manholes, and other places where, because of lack of space, or for other reasons, it is necessary to place such circuits near each other. The actual danger arises from the entrance of current and voltage from the high-voltage circuit upon the low-voltage circuit, either through a leak in insulation between transformer windings, or through a contact or connection accidentally formed between wires, thus causing a rise of potential against ground of the low-voltage circuit which may be of a dangerous magnitude unless provision is made against it. Leaks in transformer insulation appear to have been at one time the most prevalent cause of this dangerous condition, but in recent years improvements in insulation and protection by lightning arresters have reduced the percentage of failures until the greatest number of cases of the entrance of high-voltage upon low-voltage circuits seems now to be due to accidental connections between wires. In an extreme case, if a leak or a contact between wires were formed and the low-voltage circuit was not permanently grounded through a low resistance, its potential against ground might reach practically the full voltage of the high-voltage circuit, as will be shown later.

The life hazard involved here is very serious, because people are continually coming in contact with electric-light fixtures and other apparatus and appliances connected to low-voltage circuits. It is, therefore, incumbent upon persons installing such circuits to make them as nearly absolutely safe as practicable. Much can be accomplished in this respect by grounding them. This method of protection was first suggested by Prof. Elihu Thomson in 1885, who patented it and dedicated the patent to the public.

(*a*) Causes of Leaks in Transformer Insulation.—As just stated, the danger from high-voltage circuits arises in some cases because of leaks through failures in transformer insulation. The chief causes of these failures are transient electrical disturbances set up in the high-voltage line by lightning or an accidental ground, which lead to abnormal stress upon the insulation between windings. Short circuits, switching, or sudden changes in load on the high-voltage line may also set up disturbances which may

cause failures. Further causes of failures are moisture in transformer oil, inferior oil, and heating due to overloading. Moreover, it may happen that in the construction of transformers, faulty insulating material is used which is too weak to withstand indefinitely even the ordinary working voltage of the system. But because of the rigorous tests to which transformers are usually subjected before being placed in service, a failure directly attributable to initially faulty insulation rarely occurs. In nearly all cases the factor of safety of insulation between windings in new transformers for voltages up to 3500 is between five and ten.[6] In spite of this high factor of safety, however, failures of transformer insulation induced by abnormal electrical stresses and other causes are of rather frequent occurrence.

In the past, much effort has been directed toward the development of apparatus to protect the transformers of high-voltage distribution systems against lightning and other high-frequency disturbances, and as a result, several kinds of lightning arresters, chiefly of the air-gap type, have been developed which give a fair degree of protection. In fact, against anything which is of such a character as to approach a steady electric stress, these arresters afford admirable protection, but against disturbances of high frequency the protection afforded is not so complete. The chief reason for this is found in the fact that in the air-gap arresters there is an appreciable time lag in the discharge, and in the event of an electrical disturbance suddenly striking the terminals of a transformer, its full effect can be imposed upon the insulation between the windings and between low-voltage circuit and ground, before the arrester has time to act and relieve the stress. Insulation is thus pierced a number of times in succession until, finally, an electrical connection is established between windings through charred insulation or cracked bushings. The number of transformers damaged through failure of insulation amounts each year to approximately 0.5 per cent of the total number in service, varying widely, of course, in different sections of the country.

(*b*) Causes of Accidental Contacts or Connections Between Wires.—The causes of accidental contacts or connections between wires may be designated, first, as those inherent in the lines themselves and, second, as those due to outside interference. Among the first may be mentioned the blowing together of wires by the wind. This is caused, in some cases, by the fact that wires

[6] Creighton, Trans. A. I. E. E., 26, Part II, pp. 1–51.

strung from the same cross arms are likely to have different periods of vibration when set in motion. At first, when the wind commences to blow, they may swing in unison; but soon one gains on the other until, if the span is long or the sag unusually great, they may touch or even wrap around each other. In other cases where conductors cross each other with too small a clearance, a wind blowing against the lower may raise it sufficiently to touch the upper. Wires may also stretch or break under ice loads and so fall or lie upon a circuit which happens to be below them. Conductors may also part by whipping in the wind and wearing off at insulators. In extreme cases ice or wind may carry down cross arms or even poles. The observance of proper requirements as to strength and clearances of lines (see National Electrical Safety Code, secs. 22, 23, etc.), will in large measure eliminate such accidents, although to avoid breakage entirely is very difficult, because an unusual combination of conditions occasionally arises, such as heavy ice storms and high winds of great velocity, against which it is so expensive as to be impracticable to prepare.

The causes of accidental connections between wires, which may be classed as due to outside interference, are numerous, but among the most important are kites and kite wires which become entangled with electrical circuits. These may easily connect a high-voltage circuit to a low-voltage circuit and constitute a menace to life unless care is taken to obviate the danger. Falling trees, limbs, or even twigs, may also cause trouble by breaking wires or causing them to sag, or when green by forming a high resistance connection from one wire to another. The use of insulators and wires as targets for firearms is another source of danger. As mentioned above, accidental contacts or connections between wires are, at present, probably the most prevalent cause of the entrance of high-voltage upon low-voltage circuits.

(*c*) Current and Potential Relations in Low-Voltage Circuits Due to Contact with High-Voltage Circuits.—When an electrical connection is established between high-voltage and low-voltage circuits, as just indicated, the low-voltage circuit becomes, in effect, a wire tapped into the high-voltage circuit at some point and extended to every place where there are lights and other appliances. Assuming for the moment that the high-voltage line is thoroughly insulated, except where the accidental

contact under consideration has occurred, it can readily be seen by referring to Fig. 1 that the potential of the low-voltage circuit against ground depends upon the location of the point of contact. If it is at the middle of a high-voltage transformer winding, this potential will be zero, because at any instant the potential of one wire of the high-voltage line will be as much above that of the middle of the winding as the potential of the other wire is below. As the point of contact is moved away from the middle, however, the potential of the low-voltage circuit against earth increases, reaching nearly 1100 volts at the end turn. The voltage at the end turn, of course, is the same as it would be if the point of contact were at any place on the line.

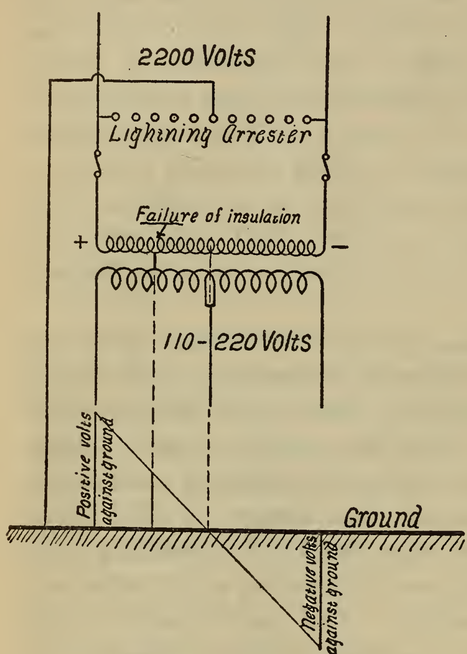

Fig. 1.—*Potential differences against ground of different points in a high-voltage winding*

If, now, an accidental ground is formed at any point on the low voltage circuit through a resistance R, current will flow into the condenser formed by the earth and the wires of the high-voltage line. The path of this current flow is represented in Fig. 2, the failure of insulation being supposed to have occurred on an end turn of the high-voltage winding, with the rest of the line thoroughly insulated. The total voltage across resistance and condenser in series is 2200, the position of the point of earth potential in the high-voltage winding depending upon the relative values of the resistance and capacity, and is, in general, no longer found at or near the middle point of the winding, as it was before the low-voltage circuit became grounded at R. It is obvious that if the body of a person were to take the place of the resistance R, the current flow might be sufficient to cause severe shock, or even death, with no other failure on the high-voltage line than the one under consideration. For this, however, the supply network would have to be several miles in length to afford

the necessary capacity between line and ground. With a 2200-volt supply system a mile in length, a current of approximately 10 milliamperes could be expected to flow, if the point of contact were at an end turn of the winding. Hence, as this current increases directly with the length of the line, a dangerous current flow would be obtained with a primary network extending over a distance of 10 or 12 miles.

Thus far it has been assumed that the high-voltage line is thoroughly insulated at every point except the one where the failure under consideration is supposed to have occurred. In actual practice, however, there is more or less leakage which combines with the capacity current and increases the total flow to such an extent that no high-voltage line can be said not to be dangerous when in contact with an ungrounded low-voltage circuit even though it is very short. The magnitude of the current flow which may take place from a 2200-volt distribution system to ground, due to capacity and leakage, is indicated by the fact that instances have been observed where a 5-ampere fuse was required to carry the current. Anything less would be blown. The lines in these cases, of course, were many miles in length and ungrounded except for the experimental ground on one phase containing the fuse.

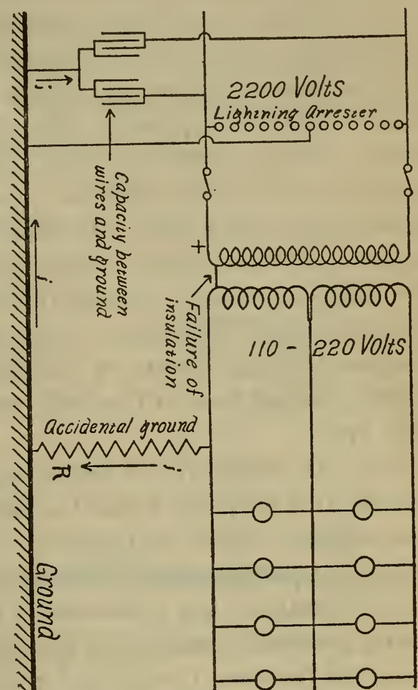

Fig. 2.—*Path of current flow with failure of insulation at end turn of high voltage winding and accidental ground on low-voltage circuit*

Aside from the leakage which may normally be expected on any extensive high-voltage system, it has been observed that there may be places where weak points in the insulation have developed, and in the event of a failure in a transformer, or a contact between wires, other failures are likely to occur elsewhere. If, therefore, in conjunction with a failure in a transformer, an accidental ground

of low resistance in comparison with the resistance R should form on the high-voltage line, the condenser represented in Fig. 2 would be, in effect, short-circuited, and a voltage would be impressed upon R which might range from zero to nearly full line voltage, depending upon the location of the points of failure in relation to each other. With the point of failure at an end turn of the transformer winding, or what amounts to the same thing, a contact between the wires of the high-voltage and the low-voltage circuits, and the accidental ground on the opposite wire of the line, 2200 volts would be impressed upon R and the accidental ground in series. This represents about the most serious condition with regard to potential difference between low-voltage circuit and ground that could arise. In this case the extent of the line would have no effect; a person occupying the position of R would receive the full line voltage, minus, of course, the drop across the accidental ground. Moreover, the danger of fire from arcing discharges through points of failure in the insulation of the low-voltage circuit due to the high voltage imposed upon it would be very great.

Now, as stated at the beginning of this part of the discussion, the life and property hazard arising from high potentials between low-voltage circuits and ground can be averted, or at least minimized, by permanently grounding some point of the low-voltage circuit through a low resistance. If this is done, and the resistance of the ground connection is low enough, no difference of potential can exist between circuit and ground which is great enough to be a serious menace to life or property. Protection is particularly easy to obtain in this manner if failure of insulation does not occur at more than one point, as set forth above. In this case—that is, with no accidental or permanent grounds on the high-voltage line—the current flow to earth is that due to the electrostatic capacity and leakage between line and ground, as represented in Fig. 2, and is relatively small.

If, however, the insulation fails at more than one point in the high-voltage circuit, or if the high-voltage circuit is intentionally grounded at another point, a condition may arise similar to that illustrated in Fig. 3, which renders protection somewhat more difficult. In this case 2200 volts are impressed upon two ground connections in series through the impedance of half of each of the low-voltage windings of the transformers. Since this impedance is small, it can be neglected for the moment, and it can be supposed

that the only check to current flow from A to B is that offered by the resistance of the ground connections. The potential difference between either low-voltage circuit and ground can, therefore, be expressed by $E=I\ R$, where I is the total current, R the resistance of either ground connection, and E the potential difference between the corresponding low-voltage circuit and ground, E being measured, of course, at some distance from the ground connection. If the resistance of the two ground connections under consideration are equal, and, as just stated, the voltage

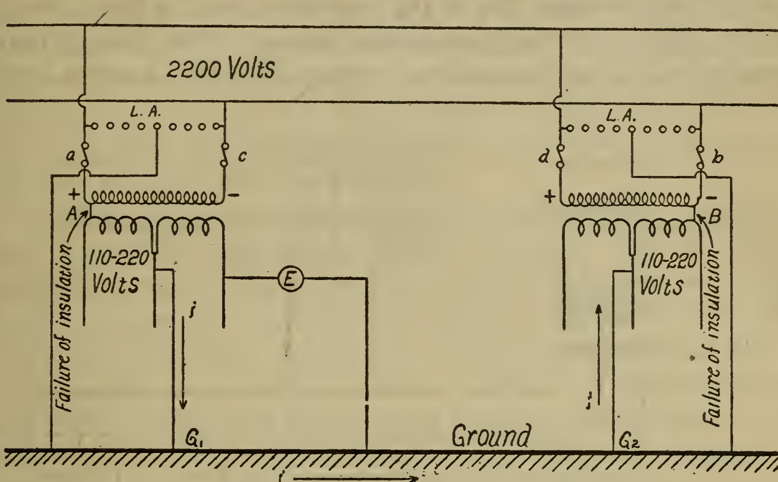

FIG. 3.—*Current from failure of insulation in two transformers flowing through ground connections G_1 and G_2 in series*

across the fault and half of the low-voltage winding is neglected, E will be 1100 volts.

As far as severity of current flow through the ground connection is concerned, Fig. 3 represents about the worst condition that could arise because of a failure of transformer insulation or a breakage of wires. But in this case—that is, where the failure is in the transformer—the current flow is limited by the transformer fuses. If the resistances of the ground connections are low enough fuses a and b will be blown when the failure occurs and break the circuit. This, of course, leaves fuses c and d intact, but the only current that can flow through the ground connections after fuses a and b are blown is that through the total impedance of both high-voltage windings in series, and this will be so small that there can be no serious rise of potential between the low-voltage circuit and ground. It should be added that the same result will be produced if one of the points of failure lies in a transformer and

the other at some point on the high-voltage line; that is, the fuses will blow and either isolate the transformer or reduce the current flow through the ground connection to a harmless amount, provided, as stated above, that the resistance of the ground connection is low enough.

With regard to accidental contacts between high-voltage and low-voltage wires, however, a condition may be presented which renders protection more difficult to obtain than either of those described above and which can be represented by connecting with a wire *A* of the same size as the line wire from the line side of the fuses in Fig. 4 to the low-voltage circuit. The flow of current through the ground connection is then definitely limited only by

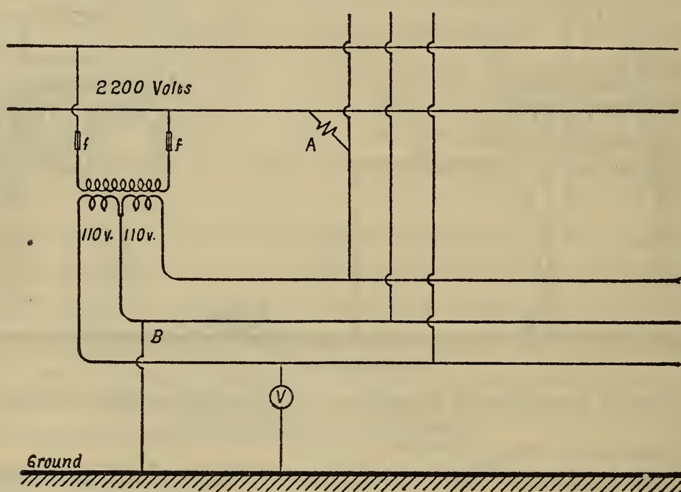

Fig. 4.—*Contact between wires*

such fuses or other circuit breakers as there are in the high-voltage line. Whether it reaches the limit set by the protective devices depends upon the current-carrying capacity of the wires, the resistance of the ground connection at *B* in series with whatever accidental grounds there are on the opposite wire of the line, and the impedance of as much of the transformer windings as happens to be in circuit. In extreme cases the current flow may easily reach hundreds of amperes.

From what has been said above, it is readily seen that, in order to avert danger from high potentials between low-voltage circuits and ground, considerable care is needed in making ground connections to secure low resistance and high-current carrying capacity. At the same time, however, it should be stated that

in all of the cases set forth above the conditions described represent the maximum degree of danger which may appear. It will sometimes occur that the points of failure in insulation will fall in such a relation to each other that the potential differences between low-voltage circuits and ground may be much lower than the full voltage of the supply system and the danger correspondingly less. But the chances that these points of failure will fall in such a relation to each other as to be harmless are negligible; and, moreover, in providing protective measures the full voltage must be taken account of because it will often be encountered. It should also be observed here that where low-voltage circuits are not protected against the development of high potentials against ground they must at all times be treated as dangerous. The frequency with which accidents occur from this cause is sufficient evidence of its seriousness.

The foregoing paragraphs apply to low-voltage circuits fed from 2200-volt single-phase supply systems with no ground connections on the high-voltage line mainly because this arrangement is simple and lends itself readily to illustrative purposes. It is a fact, of course, that a great many, perhaps a majority, of the distribution systems in use are 3 phase. These may be Y-connected 4-wire, with the neutral wire grounded either at the station, or at the station and also at intervals along the line. Or, the system may be Y-connected 3-wire with the neutral point either grounded or ungrounded. Some are delta-connected and ungrounded. But with any of these systems it is possible to have the full voltage of the primary winding of the transformer impressed upon the secondary circuit. Furthermore, if there is a permanent ground connection at the neutral point of the high-voltage circuit, there is needed but a single failure of insulation or contact between wires to produce practically full primary voltage between a low-voltage circuit and ground, and the current flow through any accidental ground or ground connection on the low-voltage circuit is limited only by the transformer fuses, or fuses in the lines, and the impedance in the circuit; that is, the condition is similar to that described above in the case of the single-phase ungrounded line where the capacity between line and ground is short-circuited by an accidental ground on one of the wires. On the other hand, with an ungrounded 3-phase system, the conditions with regard to flow of capacity current through the ground connection of a low-voltage circuit in the event of a

failure of insulation, or breakage of wires, at a single point on the line, are similar to those in the case of the single-phase circuit, only the capacity current per mile of line would be somewhat greater because of the fact that there are three wires instead of two. Moreover, with the ungrounded 3-phase system, to produce full-line voltage between a low-voltage circuit and ground requires that there be failures of insulation on more than a single wire of the circuit, the same as in the case of the single-phase system.

Before leaving this part of the discussion, it may be well to state that high voltages may appear in low-voltage circuits from causes other than faulty primary lines. The most fruitful sources of trouble of this sort are series arc circuits and street railway trolleys and feeders. Arc circuits are considered by some to be even more dangerous than primary lines, because in many cases lamps are hung from poles, necessitating bringing leads down past secondary circuits, and these lamps not infrequently fall from their brackets and bring not only the leads but sometimes a span of wire down with them. With an arc circuit in contact with an ungrounded low-voltage circuit, the difference of potential between low-voltage circuit and ground may be several thousand volts. In the case of railway trolleys and feeders, however, the greatest danger comes from the wires of low-voltage circuits breaking or sagging at crossings and resting on the railway conductors which are nearly always run underneath. Here, of course, the voltage hardly ever exceeds 550 to 700, but even voltages of this magnitude are very dangerous to life and property. Moreover, in arc circuits the current is limited to 6 or 7 amperes and hence may be taken care of by means of ground connections of only fair effectiveness without much trouble, but in railway circuits the only limits to the current are the generating capacity, the circuit breakers which are very large, and the resistance of the circuit, which makes protection more difficult. Nevertheless, by grounding those circuits with which the public comes in contact, it is possible at reasonable expense to provide a high degree of protection, not only from arc circuits but also from primary lines and railway circuits as well, and such grounding is a safety measure that should in no case be neglected.

(*d*) Point of Attachment of Ground Wires to Single-Phase Low-Voltage Circuits.—In connecting ground wires to single-phase low-voltage circuits, the usual practice is to connect to the middle wire of a 3-wire system as in Fig. 5, while with

a 2-wire system it is usually necessary to attach to one side of the circuit as in Fig. 6.[7] The chief advantage in connecting to the middle wire of the circuit lies in the fact that the voltage to earth under normal conditions of operation is then half of the total voltage. If it is found necessary to connect one side of the circuit to earth, the grounded side is at earth potential under normal conditions of operation, while the other side is at full voltage above ground. This is not a serious matter where circuits of 110 volts are concerned, but where the voltage is 220 or 440 it becomes important, and it is quite necessary for safety either that the middle point of the transformer winding be grounded, or that the circuit and apparatus and appliances connected to it be made accessible only from dry and well-insulated places, and have live parts specially guarded. (See National Electrical Safety Code, 92.)

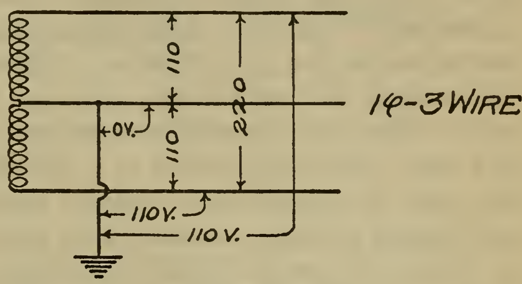

Fig. 5.—*Point of connection of ground wire to single-phase 3-wire circuits*

If a low-voltage circuit is fed by more than one transformer, a separate ground connection should be provided at each one, especially if there are junction fuses in the low-voltage circuit connecting the different transformers. Then, if the junction fuses are blown, there is no possibility of a single transformer and a part of a low-voltage circuit being isolated from the rest with no ground connection. Furthermore, ground connections may also be placed advantageously at the points where services enter buildings. These may be in addition to that at the transformer, or in lieu thereof, although the greater the number of ground connections the greater and more reliable the protection. The desirability of multiple ground connections on low-voltage

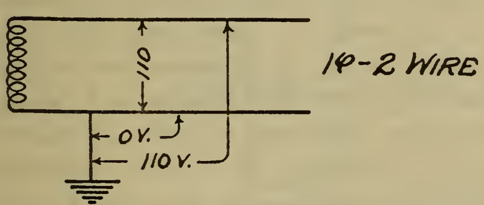

Fig. 6.—*Point of connection of ground wire to single-phase 2-wire circuits*

[7] See rule 92*b*, Appendix II.

alternating-current circuits is set forth in detail under Section IV, 5 (d).

As stated in the preceding paragraph, there should, in general, be a ground connection for each transformer. Moreover, this ground connection should be so attached that if the low-voltage circuit becomes disconnected in any way from the transformer, the low-voltage winding will still be grounded. This is particularly important if the high-voltage winding is still connected to the line, for if there is a difference of potential between high-voltage line and ground, an undue proportion of this voltage will be taken by the insulation between the low-voltage winding and case, which may result in a puncture. This is due to the fact that the electrostatic capacity between low-voltage winding and ground is small compared with that between windings—that is, if the low-voltage circuit is disconnected—and since any difference of potential between line and ground is shared in proportion to these capacities, a transient electrical disturbance on the line may puncture the insulation between low-voltage winding and case, this insulation not being designed to withstand high voltages.[8]

Mention should also be made here of the practice which is sometimes followed of using a common ground for a lightning arrester, a transformer core and case, and a low-voltage circuit. This is a good arrangement as far as the insulation of the transformer is concerned, but in the event of a discharge over the arrester, a high potential may be set up between low-voltage circuit and ground which may be a source of danger to a person touching fixtures at the time the discharge occurs. As shown more fully under Section III, 7, following, it is quite necessary to safety that a separate ground connection be provided for the lightning arrester.[9]

(*e*) POINT OF ATTACHMENT OF GROUND WIRES TO POLYPHASE LOW-VOLTAGE CIRCUITS.—In general it may be stated that in grounding polyphase low-voltage secondary circuits, an effort should be made to attach the ground wire to the point in the circuit or to the circuit wire which will give the lowest voltages between wires and ground.[10] The reasons here are the same as for single-phase circuits, and where polyphase circuits are used for

[8] P. M. Lincoln, "Grounding of Low-Tension Circuits as a Protective Measure," convention report N. E. L. A., 2, p. 324, 1911.

[9] See rule 97*a*, Appendix II.

[10] See rule 92*b*, Appendix II.

lighting and power combined, apply with even more force because of the higher secondary voltage usually involved. Figs. 7 and 8 are diagrams of some of the polyphase transformer connections in common use. The voltage between phases in each case is

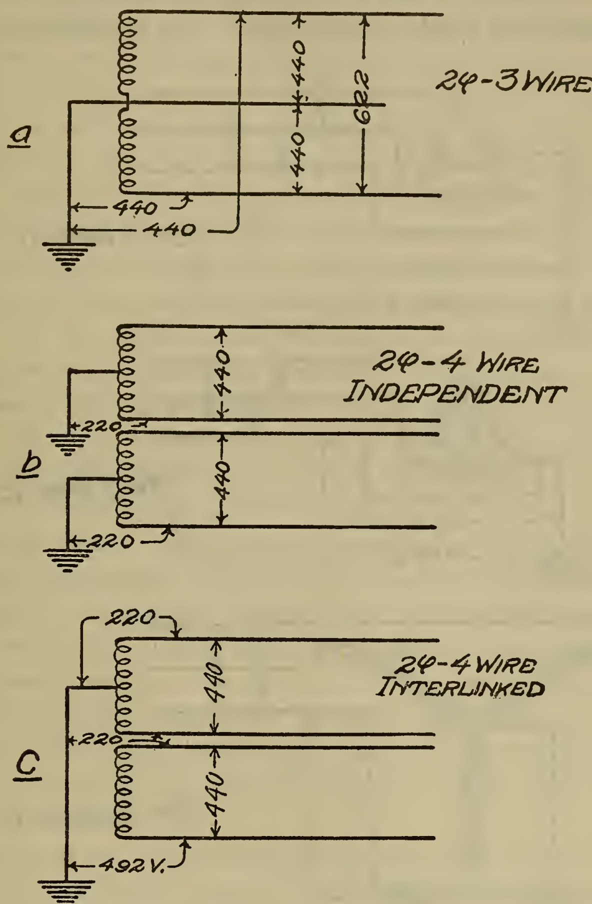

FIG. 7.—*Point of connection of ground wire to polyphase circuits*

supposed to be 440 and is chosen because it appears to be the one most commonly used in polyphase power circuits in practice, rather than because the intention is to recommend that circuits of this voltage be grounded. It may be well to mention that the National Electrical Safety Code requires that circuits in which the maximum voltage to ground does not exceed 150 be grounded, whereas grounding in the case of circuits of greater voltage to ground is left optional on the part of those responsible for them.[11]

[11] See rule 304, pt. 3, N. E. S. C.

Fig. 7, *a*, represents a 2-phase, 3-wire secondary circuit grounded at the middle wire. Here the voltage between either outside wire and ground is 440. To connect one of the outside wires to ground would put the other outside wire at 622 volts above ground, thus causing an increase in the life hazard over that obtained with a ground connection on the middle wire. Fig. 7, *b*, shows a 2-phase,

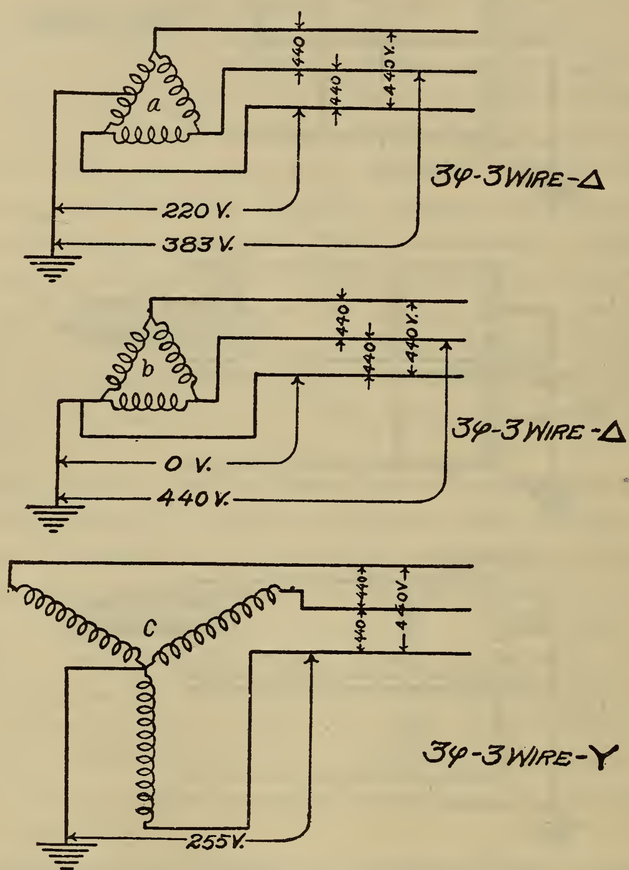

Fig. 8.—*Point of connection of ground wire to polyphase circuits*

4-wire circuit in which the phases are independent of each other. In this case the middle points of each winding can be grounded, if they are accessible, putting each of the four wires at 220 volts above ground. If the middle points are not accessible, one wire of each circuit can be grounded, which will give a voltage of 440 between each of the other outside wires and ground. In Fig. 7, *c*, the phases are interlinked within the machine taking energy from the circuit, so only one wire, or the middle point of one winding

can be connected to ground. The latter gives 492 volts between one outside wire and ground. The former gives 440 volts between two of the outside wires and ground.

In 2-phase circuits, therefore, the best points to ground are as follows: (*a*) Three-wire, at the middle wire; (*b*) 4-wire, independent, at the middle of each winding; (*c*) 4-wire, interlinked within the machine to which energy is being supplied, at the middle point of one of the windings.

In Fig. 8, *a*, is shown the secondary circuit of a 3-phase, 3-wire, delta-connected bank of transformers, such as is more or less generally used for power purposes, with the middle point of the winding of one of the transformers connected to ground. The maximum voltage to earth is 383, or 87 per cent of the line voltage. The minimum is 220 volts. In Fig. 8, *b*, is the same circuit with one corner of the delta grounded instead of the middle. Here, of course, one wire is at earth potential under normal conditions of operation, while the others are at full secondary voltage above ground. Fig. 8, *c*, represents a star-connected, 3-phase, 3-wire secondary circuit with the neutral point grounded, the voltage to ground of any wire being 58 per cent of the secondary voltage, in this case 255 volts. If the outer terminal of one of the transformers were grounded instead of the neutral point, one of the wires would be at ground potential under normal conditions of operation, while the others, as in 8, *b*, would be at full secondary voltage above ground.

In 3-phase circuits, therefore, the best points to ground are as follows: (*a*) Three-wire, delta-connected, at the middle point of the winding of one of the transformers; (*b*) 3-wire, star-connected, at the neutral point.

Fig. 9 gives some 3-phase secondary circuits not so commonly used as those mentioned above, but which are sometimes found very convenient in practice. In Fig. 9, *d*, a tap is brought out from one of the windings to give 115 volts for lighting. The most advantageous point to ground here is at the tap, because then one wire of the lighting circuit is at ground potential while the other is at 115 volts above ground. Any other point would give a greater voltage between points in the power circuit and ground, with no particular advantage in other ways. In 9, *e*, is shown a 3-phase, 6-wire, secondary circuit, sometimes installed for general utility purposes, in which the most advantageous point to ground is at the wire coming from the middle point of

one of the windings. This gives the lowest voltage to ground, amounting to practically the same thing as shown in Fig. 8, *a*. Wires 1, 2, and 3 can be used for lighting, with a maximum voltage to ground of 220, while 4, 5, and 6 may be used for power with a maximum voltage to ground of 383. Or, wires 1, 4, and 6 might

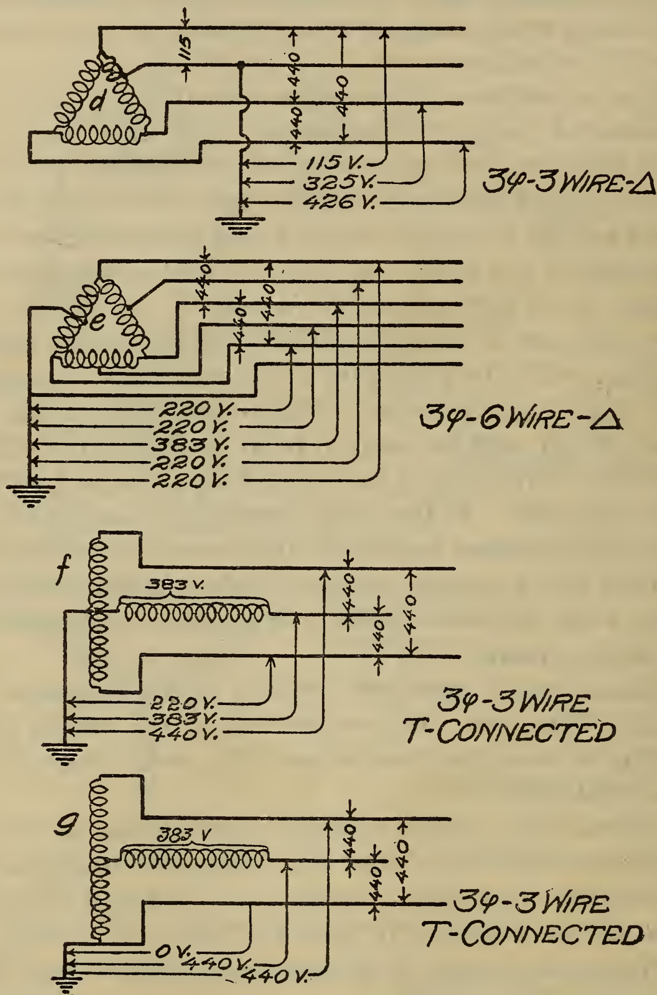

FIG. 9.—*Point of connection of ground wire to polyphase circuits*

be used for lighting with the same result. In Fig. 9, *f* and *g*, are represented the secondary windings of a set of T-connected transformers, in one case grounded at the middle point and in the other on an outside terminal. In the first, the maximum voltage to ground is 440, the minimum 383. In the second, one wire is at

ground potential, while the others are at full line voltage above ground.

To recapitulate, it appears that the most advantageous points to ground polyphase secondary circuits are as follows: (1) 2-phase, 3-wire, at the middle wire; (2) 2-phase, 4-wire, independent, at the middle point of each winding; (3) 2-phase, 4-wire, interlinked, at the middle point of one of the windings; (4) 3-phase, 3-wire, delta-connected, at the middle point of one of the windings; (5) 3-phase, star-connected, at the neutral point; (6) 3-phase, 6-wire, delta-connected, at the middle point of one of the windings; (7) where taps for lighting are taken from a delta-connected secondary, the best point is on the tap wire in such a way as to give the most favorable condition in regard to the lighting circuit; (8) in the case of the T-connected transformers, the best point is on one wire, because this wire is then placed at ground potential, whereas if connection is made to the middle point, all three wires present a high potential against ground.

It should be remembered, of course, that the real object in grounding polyphase as well as other circuits is to protect against high voltages from primary circuits and other sources, such as series arc circuits and railway conductors. There is, however, a life hazard from secondary voltages as well, and when grounding is done, this should, as indicated above, be taken into consideration and the ground connections be so disposed as to reduce it as much as practicable. It is not possible to state to what extent the life hazard from secondary voltages compares with that from high voltages but it is a fact that it gives some operating companies a great deal of concern, and they consider that much has been accomplished toward safety to consumers if in grounding to protect against high voltages the possible secondary voltage to ground due to faults in insulation is appreciably reduced at the same time. It is thought particularly important to give attention in this respect to lighting circuits taken from power-transformer installations, because here there is a possibility of dangerously high potentials appearing between the metallic parts of lighting fixtures and ground.

It may be added that there does not seem to be any possibility of an increase in the life hazard from secondary voltages in grounded secondary circuits as compared with those which are ungrounded, because, in order for an accident to occur with a grounded circuit, it is necessary for one accidental ground to appear, while with an

ungrounded circuit it is necessary for two to appear; but in the latter case, one may exist indefinitely without discovery, giving practically the same effect as a permanent ground connection, whereas in the first case an accidental ground will soon be discovered. Moreover, it is nearly always possible by grounding to reduce the potential to earth of the different wires of the circuit as compared with the potentials which might appear in the event of the formation of accidental grounds if the circuit were ungrounded.

(*f*) Effect of Resistance in Ground Connections for Low-Voltage Circuits.—From what has been said in the foregoing paragraphs it is evident that, in the event of a failure of insulation between windings in a transformer, or a contact between wires, the only definite limit to current flow to earth through the ground connection is that set by the nearest circuit breaker or fuse which will act to open the circuit. Moreover, the recognized safe maximum of potential difference between low-voltage circuits and ground, where the public as a matter of course comes in contact with apparatus and appliances connected to them, is about 150 volts. Hence, for a good degree of safety, the ground connection should be of such a character that it can carry currents ranging in value up to the limit set by the automatic circuit-opening devices just mentioned without the voltage between low-voltage circuit and ground rising to much more than 150.[12] In addition it must allow the passage of this current for a considerable period without an appreciable rise in its resistance, which would tend to increase the voltage between low-voltage circuit and ground. As shown below, the maximum resistance which will permit the fulfillment of these requirements can be readily ascertained.

In doing this, however, allowance should be made for the variation of resistance of ground connections with the temperature and moisture content of the earth The results of tests given hereafter will show that this variation from time to time may in some cases be as much as several hundred per cent, so when ground connections are installed it is advisable to allow a factor of safety to care for this contingency. The value of the factor to be used for any ground connection depends upon seasonal conditions; when made in very wet seasons a factor of safety of 3 may be used, whereas in very dry or very cold seasons 1 or even less may be acceptable. With a factor of safety of 1, the limit of voltage

[12] See rule 94*a*, Appendix II.

E in Fig. 3 at the time of installation would be 150. The maximum allowable resistance of the earth connection at the time of installation can, therefore, be expressed by $R = 150/Ia$, where Ia is the current rating of the nearest circuit breaker which will act to open the circuit in the event of an accident to insulation. If this current were 3 amperes R would be 150/3, or 50 ohms, 10 amperes 15 ohms, 100 amperes 1.5 ohms, and so on.

From these figures it may readily be inferred that little difficulty will be experienced in obtaining a good degree of protection by the use of ground connections where transformers and high-voltage lines of limited kilowatt capacity are concerned. But for high-voltage lines of large capacity, especially where contacts between wires are to be guarded against, it does not seem practicable to provide ground connections of such a character as entirely to avert danger under all conditions, unless connections to water pipes are used. In fact, to connect to water pipes is advantageous in any case and where there is opportunity for such connections their use is strongly to be recommended. The relative merits of water pipe ground connections and other forms are discussed in Section IV of this paper.

2. DIRECT-CURRENT DISTRIBUTION SYSTEMS

Direct-current distribution systems can be definitely divided into three classes so far as grounding is concerned, namely, trolley systems, 2-wire systems, and 3-wire systems. Trolley systems, of course, are not grounded, at least not in the sense implied by the term "protective grounds," so they do not need further discussion. In the other two, the purposes for which ground connections are used are, in the main, somewhat different and it is therefore desirable to consider them separately.

(*a*) Two-Wire Systems.—In 2-wire systems, the regular practice has developed of insulating the lines throughout and using ground connections only for the purpose of detecting accidental grounds. The reasons for this are as follows: If a 2-wire system is grounded it is generally necessary to attach the ground wire to one side of the circuit, and as pointed out above, this side is then at earth potential while the potential difference between the other wire and earth is equal to the full voltage of the line. A person touching this other wire would, therefore, receive the full line voltage of 110 or 220 volts as the case might be. This, however, is all that could occur under any condition of accidental

grounding on a circuit intentionally insulated, while during the time the insulation remained in good condition there would be no danger to life or property. As a consequence, unless the circuit is so situated that it may become crossed with high-voltage lines, there is no life hazard presented with it insulated that is not also presented with one wire connected to ground. Moreover, with one side grounded, only one accidental ground is necessary to bring about suitable conditions for starting a fire or producing electrolysis troubles, while with the circuit insulated an accidental ground on each wire is necessary to start a fire or give rise to danger of electrolysis. It may also be said that there is less danger of accidental grounds with the circuit insulated than with it grounded, for in the first case the stress on the insulation is shared by the two sides in series, while in the latter the full voltage of the line is taken by the insulation of one side, but the difference seems to be so small that it is of no practical consequence. Hence, since so little is to be gained by grounding 2-wire systems, they are in most cases insulated throughout and ground connections used only for the purpose of detecting accidental grounds.

The foregoing statement must be qualified, however, by adding that on a circuit which is completely insulated there is danger of an accumulation of static electricity of sufficient voltage to puncture insulation, and to remove this some form of ground connection is needed, but such ground connection may be of very high resistance. In fact, it will in most cases be found that the connection to earth formed by the ground detecting device will obviate all danger from static electricity. A further qualification is that if the circuit is exposed to contact with high-voltage lines it must be grounded as thoroughly as though it were an alternating-current secondary circuit fed from a high-voltage distribution system.

(*b*) Three-Wire Systems.—In the 3-wire system of direct-current distribution the extent of the lines is in most cases greater, and the total voltage higher than in 2-wire systems. The life and fire hazards presented by the usual 3-wire system are, therefore, appreciably greater than in the usual 2-wire system, and greater precautions are necessary to prevent accidents. On the other hand, the 3-wire system lends itself more readily to precautionary measures than the 2-wire system, in that the middle wire can be, and usually is, grounded, placing it at earth potential and making the potential difference between either outside wire and earth equal

to half of the total voltage. With the circuit insulated throughout, however, an accidental ground on one of the outside wires would put the other outside wire at full voltage above ground. If an insulated 3-wire circuit accidentally becomes grounded on one of the outside wires, there is, therefore, considerable danger to life as well as property, especially if the total voltage is 440, as it is in some instances. With the middle wire permanently grounded, there is, of course, still danger to property if an accidental ground forms on one of the outside wires, but if the resistance of the ground connection is low, an accidental ground does not appreciably increase the life hazard. Nevertheless, in the case of 440-volt circuits, the question of whether the life hazard presented by 220 volts continuously present between outside wires and ground is greater than that presented by the possibility of an accidental ground forming on an outside wire is at present unsettled. Hence, it has been deemed wise in preparing rules in regard to the grounding of circuits to require grounding only where the voltage to ground of any point of the grounded circuit does not exceed 150, and to leave cases where the voltage is greater to be grounded at the option of those responsible for them.[13]

The resistance of ground connections for 3-wire systems should be made as low as practicable. In fact, the lower this resistance is the better, and a perfect condition would be obtained only where the resistance to flow of current from the middle wire into the earth is zero. Zero resistance is, of course, not obtainable in practice, but by making use of water pipes or other available underground metallic structures a very low resistance (usually less than one ohm) can be realized. It should be stated here, however, as will be pointed out later, that it is advisable to ground the middle wire at but one point, and that at the station.[14]

The reasons for low resistance in ground connections for 3-wire systems are as follows: In the first place, 3-wire systems may in some cases become crossed with high-voltage lines, so a low resistance is desirable to prevent an undue rise of potential of the system against ground in the same manner as for low-voltage alternating-current circuits fed from high-voltage distribution networks; in the second place, one of the objects in grounding the middle wire of a 3-wire direct-current system is to keep the potential difference between either outside wire and ground as near half of the total voltage as possible. Now, if one of the outside

[13] See rule 304, pt. 3, N. E. S. C. [14] See rule 92*a*, Appendix II, N. E. S. C.

wires becomes accidentally grounded, current will flow through this accidental ground and the ground connection in series to the middle wire, as shown in Fig. 10, the normal potential difference between middle and outside wires being shared by the accidental ground and the ground connection in proportion to their respective resistances. The potential difference between the ungrounded outside wire and ground is evidently the sum of the potential differences between this wire and the middle wire and across the ground connection, this potential being measured at some distance from the ground connection as indicated at E in Fig. 10. Now, if the resistance of the ground connection is low, and that of the accidental ground high, there will be very little unbalancing of the potentials to ground of the two outside wires. These potentials will remain practically the same as under normal conditions

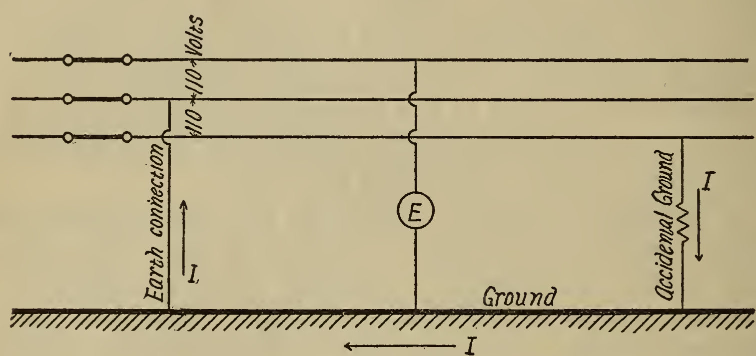

FIG. 10.—*Accidental ground on 3-wire direct-current system with middle wire earthed*

of operation. But if the resistance of the accidental ground is low, there may be considerable unbalancing of the voltages, not only between outside wires and ground, but also between wires if there is heavy current flow in them. Here service can be restored only by clearing the accidental ground, and in the meantime the line should be cut out manually if the automatic circuit-opening devices do not operate. On the other hand, if the resistance of the ground connection is high, there will be marked unbalancing of the voltage between outside wires and ground whether the resistance of the accidental ground is high or low. Hence, to minimize the bad effects of accidental grounds requires that the resistance of the ground connection be low. If it were of zero resistance, of course, there could be no unbalancing of voltages due to accidental grounds other than that attendant upon heavy current flow in the wires, and the nearer the resistance of the

ground connection approaches zero the more nearly the balance of the system will be maintained under all conditions of accidental grounding. The nearest approach possible to a ground connection of zero resistance is by connecting with a heavy cable to a large water main, which, in the case of most direct-current central stations, is not difficult of access.

3. DETECTORS OF ACCIDENTAL GROUNDS

The detection of accidental grounds is an important part of the operation of low-voltage distribution systems. Such grounds do not become apparent at once by affecting the operation of the system, and special means must, therefore, be resorted to in order to detect them. This is the case especially with direct-current distribution systems. The necessity for detecting these grounds arises from the life and fire hazards which they involve, and in direct-current circuits the possibility of electrolysis, but chiefly the fire hazard. The life hazard is not great because very special conditions are necessary to cause severe injury or death with 110 or 220 volts. Nevertheless, such accidents have occurred, mostly to persons who were at the time in damp locations, so the life hazard must be considered. In addition, if accidental grounds develop and remain undiscovered for a time, the resulting loss of energy, if the grounds are of low resistance, may become an important matter because the wasted energy must be paid for by either the consumer or the central station, depending upon the location of the points of failure of insulation with respect to the consumer's meter.

(*a*) Two-wire, Direct-Current Distribution Systems.—In the usual method of detecting accidental grounds on 2-wire direct-current systems a resistance sufficiently great to make the current flow through it small is connected across the line at the station and the middle point of this resistance connected to earth. Ordinarily there is no flow of current in the ground connection. If, however, an accidental ground develops on one side of the line, one-half of the resistance connected across the line is shunted by the ground connection in series with the accidental ground. Current then flows through the accidental ground and the ground connection to the opposite side of the line, causing the current flow in the two parts of the resistance just mentioned to become unequal; and by the use of suitable current measuring devices, not only can the presence of the accidental ground be

discovered, but also the side of the line on which it has occurred. The method would fail if accidental grounds of equal resistance should develop simultaneously on each wire, but the possibility that both grounds would be of the same resistance is exceedingly remote, and if there were a difference of resistance, the presence of grounds would be indicated. In any case the current flow carried by the ground connection of the detector is relatively small, being usually of the order of an ampere, and the resistance is, for that reason, not an important matter. The lower the resistance of the ground connection of the detectors, however, the better, because, with a low resistance, incipient grounds on the line can be more readily detected. The maximum allowable resistance would depend upon the character of the current measuring device used, and in every case where ground detectors are installed tests should be made to make certain that the resistance of the ground connection is of such a value as to make the device work properly.

The preceding paragraph applies to 2-wire, direct-current systems which are not grounded to protect against high voltages. Where such protective grounds are used, they will, as stated heretofore, generally be connected to one side of the line. Here one wire is at earth potential, so any accidental grounds that may form upon it are of no practical consequence. To detect accidental grounds on the other wire it is only necessary to ascertain when current is flowing in the ground wire, since when such grounds develop, current flow will take place through them and the ground connection in series to the opposite side of the line.

(*b*) Three-Wire, Direct-Current Systems.—With the middle wire of a 3-wire, direct-current system grounded at a single point there is, ordinarily, no flow of current through the ground connection. If, however, an accidental ground should develop on an outer wire, current would flow through this accidental ground and the ground connection in series to the middle wire, the direction of flow depending upon whether the positive or negative side of the line had become grounded. In order to detect accidental grounds, therefore, it is only necessary to ascertain when current is flowing in the ground wire; its direction tells which side of the line the accidental ground is on. As in the 2-wire system without protective grounds, however, if accidental grounds of equal resistance should develop simultaneously on both sides of the circuit the method would fail, but the chances that this would occur are extremely small.

(*c*) Low-Voltage, Alternating-Current Systems.—In low-voltage alternating-current circuits which are permanently grounded at a single point, it is possible to detect accidental grounds in much the same way as in direct-current systems; that is, in 2-wire systems permanently grounded on one side, to detect accidental grounds on the opposite side, all that is necessary is to ascertain when current is flowing in the ground wire. If the middle point of the transformer winding is connected to ground, the same is true, but here the accidental ground may be on either wire and there is no way of telling which because there is no distinction as to direction of current flow. This also applies to a 3-wire system with a ground connection on the middle wire. In either case, however, if the current flow through the ground connection is heavy, it is possible to ascertain which wire the accidental ground is on by connecting a voltage-measuring device across each half of the transformer winding. The side on which the accidental ground has occurred will show a lower voltage than the other on account of the heavier current which it is carrying. In a 3-wire system there may be a difference of voltages due to an unbalanced load, but with current flow in the ground wire and a marked difference in voltage between the two sides of the line at the same time, it may safely be inferred that there is a serious accidental ground in existence on the side showing the lowest voltage.

With multiple grounds on the system the current flow due to accidental grounds is divided among the various ground connections in inverse proportion to their resistances. This makes detection of the accidental grounds rather difficult, especially on circuits having many points of connection to earth, because, even though an accidental ground of low resistance exists, if the current is divided among a hundred or more paths, it will not be easily distinguished from the small currents which always arise in ground wires from the fact that the permanently grounded conductor of the circuit operates in parallel with the ground connections; and when current flows in the grounded conductor, more or less current also flows through the ground.

Now, as pointed out later in a section devoted to multiple grounds, this current flow is of no importance save as it interferes with the detection of accidental grounds, but here its effects are of sufficient importance to prevent in a large measure the use of special ground-detecting devices in low-voltage alternating-current

circuits. In fact, in combination with other circumstances, it has made the use of these special ground detectors in practice the exception rather than the rule. For the most part, the development of accidental grounds is left to make itself apparent in meter readings, by blowing fuses, or by electric shocks to persons. In every case where it is practicable, however, such slipshod methods should be done away with and more suitable methods adopted instead.

When once an accidental ground has made itself apparent, it often turns out that it is in the customer's premises, where the electric utility has no power to remove it. The remedy lies with the consumer, and unless he sees that it is to his own advantage to apply it, the utility may have to choose between either discontinuing service until such time as the consumer becomes amenable to reason, or continuing it by cutting off all protective grounds and operating with the accidental ground still in existence. Since the utility usually does not wish to lose a customer or incur unfavorable public opinion by cutting off the service, the latter course is frequently followed. Temporarily this may be well enough, because it is not always possible for a consumer to clear accidental grounds immediately on discovering them, but in many cases, once the protective grounds are cut off, they are never reconnected. Such a condition should not be allowed to exist, for, in the first place, the consumer is in danger of fire in his premises and of electric shock to his family or employees. Moreover, although cutting off the ground wires may for the time being obviate the annoyance of running up large bills for wasted electrical energy, there is a possibility that an accidental ground may form on the other wire and run up a bill even while the consumer is dwelling in fancied security. In the second place, the use of protective grounds is a safety measure so well recognized in electrical practice that an accident in the consumer's premises while protective grounds are absent not only puts the electric utility in a bad light before the public, but puts it at a great disadvantage in the event of a damage suit ensuing. In view of these things, it is evidently to the great advantage of both consumer and utility that the accidental grounds be removed within a reasonable time.

It is, of course, out of the question to expect utilities to take drastic action in a case of this kind, and it is strongly to be urged that legislative bodies make rules requiring that service be cut

off unless circuits are put in operating condition within the time required to get the work done. The cost of finding and removing such accidental grounds may not be inconsiderable in some cases, but in the average case an electrician with a "megger," or other device for measuring the resistance of insulation, can search out and clear an accidental ground in a few hours at most. The cost is not to be compared with that which might result in a case of fire or personal injury.

4. MACHINE FRAMES

If the frame of a dynamo-electric machine is insulated from ground, and an accidental contact should occur between the frame or armature core and some part of the electric circuit, such as the armature winding, there would, in general, be a difference of potential between the frame and ground. The value of this difference of potential might be anything between zero and nearly full machine voltage, depending upon the location of the point of failure of insulation in the internal circuit and the condition of insulation of the external circuit. In the case of high-voltage machines with insulated frames, therefore, and also in the case of low-voltage machines which are connected through transformers to high-voltage circuits, a very serious risk to the lives of attendants is presented by the possibility of accidental grounds in the machines; and in order to avert, or at least greatly to reduce, this danger, the frames of such machines should be grounded. In fact, if the elimination of life hazard were the only factor to be considered, it would be best to ground the frames of machines of all kinds, mainly for the reason that there is great uncertainty as to the maximum voltage which is not dangerous to life. This, however, is not the general practice; and, moreover, it is a matter of common knowledge that in many cases even high-voltage machines are operated with insulated frames, except where rules are in force which require the grounding of the frames of all machines but those operating under special conditions. Such rules are in some cases included in city ordinances; in others fire insurance companies have certain rules, such, for instance, as the rule of the National Fire Protection Association which requires that the frames of machines operating at more than 550 volts be grounded, and that the frames of machines operating at 550 volts or less be grounded wherever feasible, or, if not feasible, that they be permanently and ef-

fectively insulated. Where companies operating machines assume the fire risk, and are not subject to regulations similar to those mentioned above, it not infrequently happens that machines of even very high voltage will be found with insulated frames. In view of the life hazard involved, this practice should be discontinued.

(*a*) Insulated Frames.—The argument presented in favor of insulated frames is that such insulation safeguards machines and assists in maintaining continuity of service. Grounding frames is said to militate against safety of machines and continuity of service in the following ways: In the first place, it increases the stress on the insulation between electric circuit and frame, the voltage to ground with a grounded frame being taken entirely by the insulation of the electric circuit, whereas with the frame insulated the voltage to ground is shared by two layers of insulation in series, viz, the layer between circuit and frame, and the layer between frame and ground. The share of the total voltage taken by each layer is in direct proportion to its insulation resistance. Accidental grounds from failure of insulation, therefore, appear to be more likely to occur in machines with grounded frames than in machines with insulated frames. In the second place, with a grounded frame, an accidental ground in a machine may result in damage if there is an accidental ground or a ground connection in the external circuit, while on the contrary, if the frame of the machine were insulated, no damage would occur. This is said to be particularly the case with railway power-plant machinery feeding energy into a trolley system with ground return, and to a considerable degree, at least, with electrical machinery of all kinds.

It must be granted that the foregoing statements appear to be, in part at least, true; that is, in general, grounding frames increases the probability of damage by accidental grounds and this to the greatest extent in high-voltage machines. The principal reason for the latter is that in low-voltage machines and lines the factor of safety of insulation is relatively high—that is, as far as normal operating conditions are concerned—while on the other hand, in high-voltage machines and lines the factor of safety of insulation is much less, and in fact, may be said to decrease as the voltage increases. It is true, of course, that in low-voltage circuits the high factor of safety mentioned above is offset to a certain extent by ground connections in the external circuit, whereas in high-voltage circuits the total stress is in many instances shared

by the insulation of lines and machines in series. It is also true that the insulation of high-voltage circuits is less susceptible to damage by surges and high-frequency electrical disturbances than is the insulation of low-voltage circuits. However, because of the great disparity between high-voltage and low-voltage machines and lines as regards the factor of safety of insulation, and also because the insulation of high-voltage circuits is the most exposed to damage by electrical causes, there is no doubt that with grounded frames high-voltage machines are the most likely to be damaged, although it is not possible to say what the difference may be. Moreover, after an accidental ground has formed to a grounded frame, the resulting current flow to earth is the more destructive the higher the voltage of the machine, since it usually occurs that the higher the voltage the larger the kilowatt capacity and hence the greater the power for destruction. Insulating frames, therefore, appeals very strongly to many operating companies as a means of safeguarding their property and service, especially to railway companies, since, as just pointed out, railway power-plant machinery is by some considered to be more than ordinarily susceptible to the kind of damage described above.

With regard to life hazard, however, the opposite is the case; that is, with insulated frames the life hazard increases as the voltage increases. It is possible, of course, with insulating platforms and other devices to avert danger from this source, and the faithful observance of their use will result in a great degree of freedom from accidents. At the same time, safety here depends upon individual memory and carefulness, and in a case where the frame of a machine is in a safe condition for months or even years at a stretch, the observance of precautions in respect to it inevitably becomes lax. It is evident, therefore, that the best degree of safety lies in preventing a rise of potential between frame and ground by grounding the frame. Such grounding should be extended to machines of all voltages because, as previously stated, there is great uncertainty as to the maximum voltage which is not dangerous to life, although an exception may be made in the case of machines operating on lines supplying power at 150 volts or less which are not liable to contact with high-voltage lines. An exception may also be made in the case of machines where it is necessary to work on brushes when they are alive. But no exception can be made where machines of any kind operate in explosive gas or in very damp places; the frames here should in every case be grounded.

Now, in support of grounded frames there are several points which may be urged in addition to that of the safety secured to attendants. In the first place, whether in many cases insulating frames decreases the stress on the insulation of the circuit to an appreciable degree is open to question. For, in order that such insulation may reduce the stress on the insulation of the circuit, it is necessary that the insulation resistance between frame and ground be comparable in magnitude with that between circuit and frame, and unless it is, the benefits derived from insulating the frame are negligible as far as stress on insulation is concerned. In fact, if the resistance of the layer of insultation between frame and ground is low in comparison with that between electric circuit and frame, the frame might practically as well be grounded. There are, of course, certain types of machines, such as old type arc machines, in which the resistance of the insulation between electric circuit and frame is low, and here insulation between frame and ground would be of assistance, but such cases are exceptional. In the second place, insulating frames is conducive to carelessness in operation in that machines can be operated with an accidental ground to the frame or armature core, which is contrary to sound engineering practice. It enables the time of making repairs to be put off, and if the time of repairing can be put off at all, it will in many cases be postponed until something further happens, usually a second ground in the machine which may lead to damage of a more severe character than that produced by an accidental ground to a grounded frame. Furthermore, with insulated frames, accidental grounds are likely to develop without the knowledge of attendants, unless special means are taken to detect them. This is not often done, and incipient grounds may exist unsuspected until a burn out of the machine or a fatal, or at least serious, accident discloses the faulty condition.

On the other hand, without an appreciable increase of expense for operating purposes, machines with grounded frames can be safeguarded to an even greater extent than would ordinarily be the case with insulated frames, for with grounded frames devices continuously in operation for detecting incipient accidental grounds can be used, and in addition, tests can be made periodically which will show any progressive weakening of insulation. Incipient failures can thus be detected, searched out, and removed before anything serious happens, and in the meantime, the grounded frame guarantees safety to attendants from accidental

grounds which form without warning. In short, there is, in general, no advantage obtained in operating machines with insulated frames that can not also be had with grounded frames if a reasonable degree of care is used, and with grounded frames there is the additional great advantage of reduced life hazard.

To ground frames, however, may not in every case reduce the life hazard. Reference is had to one of the exceptions mentioned above, viz, where it is necessary to do work on the brushes of machines while they are alive. Here it is very easy for an attendant to come in contact with brushes and frame simultaneously with consequent danger to his life if the frame is grounded, but if the frame is insulated and an insulating platform built around it, the danger is reduced. With a grounded frame, even though an insulating platform is built around it, an attendant touching brushes and frame at the same time is liable to receive current not only from accidental grounds in the machine but also from accidental grounds on the external circuit, whereas if the frame is insulated, the danger arises only from accidental grounds in the machine. Hence, where it is necessary to work on the brushes of machines while alive, the best procedure seems to be to insulate the frame and build an insulating platform around it. On the other hand, where it is not necessary for attendants to come in contact with the electrical circuits of machines while they are alive, it seems better to ground the frames, mainly because there is then no possibility of an accident through carelessness.

(*b*) Ground Connections for Frames.—The resistance of earth connections for machine frames to give the best degree of safety can be determined in much the same way as for low-voltage alternating-current circuits; that is, it must be such that with a current flow to earth equal to the rating of the nearest circuit breaker which will operate to open the circuit to the machine in the event of an accident to insulation, the potential difference between frame and ground will not rise to a dangerous value. This rule can not be held to arbitrarily in all cases, however, because it may occur that soil and other conditions are such that a sufficiently low resistance to comply with the rule is impracticable of attainment, or it may be that an earth connection of very low resistance will result in unnecessary damage to a machine in the event of a failure of insulation. In such cases an approximately equivalent degree of protection to life can be obtained by making the resistance of the earth connection as low

as practicable and adjusting circuit breakers and other devices in such a way that, if current of a predetermined value flows to ground, the machine will either be cut out of circuit or insulated from ground by opening the earth wire. If the latter alternative is chosen warning can be given that the machine is in a dangerous condition, and it can be operated with due caution until it can be shut down for repairs. It should be emphasized here that under no consideration should a machine with an accidental ground to the frame be operated longer than is absolutely necessary.

5. CONDUCTING BODIES INCLOSING OR NEAR ELECTRICAL CIRCUITS

Coming under this head are those conducting bodies which, like machine frames but, in general, of less importance, are dangerous to life or property because of their proximity to electrical circuits. They may be enumerated in part as follows: Transformer cases, switch cases, cabinets, conduit, switchboard frames, cable armor, piping, in fact any metallic body inclosing or near an electrical circuit which is accessible to persons or is in a place where there are inflammable substances. On account of the great number of cases which would come under this head, they can not all be discussed in detail, but general principles can be pointed out and detailed discussion given to some of those which seem most important.

Danger from the conducting bodies under consideration may arise in two ways: In the first place, accidental contact may occur between the body and the electrical circuit, causing the body to become virtually a part of the electrical circuit unprotected by insulation. This is most likely to be the case with the conducting bodies which are in very close proximity to electrical circuits, particularly those which may, in strictness, be designated as metallic inclosures for electrical circuits, which include transformer cases, switch cases, cabinets, conduit, and cable armor. In the second place, persons may come in contact with electrical circuit and conducting body at the same time, or allow tools or other conducting objects to do so, which may, by arcing, cause shocks, burns, or fires. Accidents of this kind are most common with switchboard frames, piping, and structural metal. Of course, for such accidents to occur it is necessary for the electrical circuits to have bare, or at least unguarded parts.

(*a*) Danger from Accidental Contact Between Metallic Bodies and Electrical Circuits.—In the case of accidental

contact between electrical circuit and conducting body the body takes the potential against ground of that part of the electrical circuit with which it is in contact. Moreover, unless the conducting body—that is, the transformer case, switch case, conduit, or whatever it may be—is intentionally grounded it is more than likely that it will simply be electrically isolated from ground. In other words, it will be connected to earth through a resistance of hundreds or perhaps thousands of ohms, instead of a few ohms, as it would be if it were grounded, or millions of ohms, as it would be if it were insulated from earth. Hence, if the condition of insulation of other parts of the circuit is such as to permit the flow of current, and the potential differences between electrical circuit and ground are such as are commonly found in practice, not only will the conducting body be at a potential against ground which may in many cases be dangerous to life, but there will be a flow of current to ground through the leakage path which may easily be the cause of fire through heating of inflammable substances if there are any present.

As an example may be taken a conduit through which passes a 440-volt, 3-wire, direct-current circuit with the middle wire grounded at the station, the conduit being isolated from earth by means of wooden or other inflammable supports as in a frame building or studded partition. In this case, if one of the outside wires should come in contact with the conduit through dampness or some other cause, the conduit would be at a potential of approximately 220 volts against ground. Current would then tend to flow through the accidental ground to the conduit and from there to earth through the leakage path and to the middle wire through the ground connection at the station, or to accidental grounds on the other outside wire of the line if there were any. If the resistance of the leakage path between conduit and ground were a few hundred ohms, heating might occur at points to a sufficient degree to cause fire, with a current of as little as an ampere or so. A current of this magnitude would easily escape notice even though ground detectors were used, and would be extremely likely to, if there were accidental grounds on the other outside wire, since grounds on both outside wires would tend to produce zero current in the ground connection. In the meantime a person touching the conduit would be likely to receive a severe shock if the locality were damp, or if for other reasons a good connection to earth were formed in some way through the body. Varying degrees of these dangers are presented by every ungrounded metallic inclosure

for electrical circuits and by all metallic objects near electrical circuits, being dependent upon the voltage of the circuit, its condition of insulation, and other factors. The frequency with which fires and electrical shocks due to this cause are reported is sufficient evidence of its seriousness.

The remedy for the condition described above as dangerous, is obvious; that is, to ground the conducting body. This rule is embodied in the rules of the National Electrical Safety Code, and also in those of the National Fire Protection Association. The latter rules are already enforced by underwriting inspection bureaus and municipal inspection bureaus wherever they have jurisdiction, but outside of these jurisdictions, unless regulations of similar character are enforced by other agencies, precautions against fire or accident are in many cases neglected.

Grounding the conducting body serves two purposes: In the first place, it allows sufficient current flow in the event of an accident to insulation to insure positive operation of ground detecting devices; in the second place, it tends to prevent the potential between conducting body and ground from rising to a dangerous value, and in addition, if the resistance of the ground connection is low enough, will serve to cut out a faulty circuit through the operation of fuses or circuit breakers. Thus, in a branch circuit fused for 6 amperes an accidental ground would result in a blown fuse if the voltage imposed were 150 and the resistance of the ground connection were as much as 20 ohms. With a branch circuit fused for 10 amperes, the resistance of the ground connection to produce a similar result would have to be 12 ohms, and so on.

It is readily seen that to produce results of this kind in circuits of large current-carrying capacity requires very low resistance in the ground connection, and here water pipes are of service. By their use a high degree of protection is obtainable. Where they are not available, however, other types of ground connections must be resorted to, but in nearly all cases a fair degree of protection can thus be obtained at reasonable cost.

(*b*) Danger from Contact with Electrical Circuit and Metallic Body at the Same Time.—With regard to conducting bodies near electrical circuits which are dangerous because persons may come in contact with conducting body and electrical circuit at the same time, or allow tools to do so, it may be said that such bodies should either be covered with a semi-insulating

material or isolated from earth, depending upon which is practicable; or both if necessary to obtain a minimum life and fire hazard. If, on the other hand, there is also danger that the conducting body may accidentally come in contact with the circuit at some point, it would probably be better to ground it, and, in addition, inclose those parts giving rise to the danger mentioned above with semi-insulating material or prevent contact in some other way. Where the sole danger, however, is from contact with persons or tools, isolation, where practicable, will undoubtedly be found to give the necessary degree of protection. This does not apply, of course, to metallic bodies which are of such construction that isolation is impossible, as it may be in the case of piping or structural metal. In such cases the desired protection can undoubtedly best be obtained by insulating or inclosing the metal with plaster or other fireproof material of considerable electrical resistivity.

The degree of protection obtainable where the circuit must be left exposed near the conducting body depends to a large extent upon the voltage of the circuit. In the case of low-voltage circuits where much work is done on lines and switchboards while circuits are alive, the greatest danger is from arcs formed by getting tools across the line or from line to a metallic body near by, more particularly the latter, because in respect to such conducting bodies there is naturally less care exercised than in the case of the line wires. If the metallic body is grounded, even through a considerable resistance, a severe burn may result; whereas, if the body is isolated—that is, separated from earth by a resistance of even a few hundred ohms—the flow of current would be insufficient to form an arc. Isolating, or covering with isolating material, therefore, gives a high degree of protection. In the case of high-voltage circuits, however, isolation can not always be depended upon for protection, but it is useful in many places. Moreover, the same necessity for the use of isolation does not appear for the reason that the circuits, in ordinary circumstances, should not be approached while they are alive. If work is to be done, they should be killed and securely grounded. Nevertheless, many times this precaution is frequently disregarded, or work is done on dead lines near lines that are alive, and under such circumstances the proximity of metallic bodies presents a certain degree of danger. There is also some danger, of course, even when working on lines supposedly killed and

30263°—18——4

grounded, because if a mistake is made and the line switched in, there may be a difference of potential against ground sufficient to be dangerous in spite of the ground connection. In any case, therefore, it is a wise precaution either to isolate such conducting bodies with the highest resistance practicable or secure them from contact with a covering of insulating or semi-insulating material, especially in places where work is often done.

(*c*) Railway Power-House Switchboard Frames.—One of the most important examples of a conducting body near an electrical circuit which may give rise to danger is that of the frames of certain types of railway power house or substation switchboards. At present it is a common practice among railway companies to ground these frames. This means, in the case of single trolley systems with ground return, virtually connecting the frame of the switchboard to the negative bus bar of the generating system. This by some is said to "fix" the potential of the frame. There is no doubt that the potential of the frame is "fixed" in this way, but a very undesirable thing is accomplished at the same time, namely, the positive bus bar and the frame are put in such relation to each other that in the event of a metallic connection being made between them the only limit to current flow is that placed by the generating capacity of the system and the current-carrying capacity of the circuit so formed. Now, in railway work it is sometimes very necessary to do repair work on switchboards while the conductors are alive, and in doing such work tools are likely to slip—in fact, sometimes do slip—and make contact with positive bus bar and frame. The heavy current flow which invariably follows causes an arc of tremendous size to form, and in many cases workmen have been either burned to death or maimed and disfigured for life. There is also a possibility of severe electrical shocks, although this is a minor matter compared with the effects of burns. Experience shows that the great majority of accidents on railway switchboards consist of burns received through short circuits between the positive bus bar and a grounded switchboard frame. In view of the consequences of such accidents, the grounding of the frames of those types of railway power-house switchboards in which the bus bars are exposed and sufficiently close to each other, or to the frame, to permit short-circuiting by tools of ordinary length must be regarded as increasing the hazard and should be discontinued. The potential of the frame can be just as definitely

"fixed" by mounting the frame on a concrete base as by grounding, concrete being a semi-insulator when air-dried. There is, then, a high resistance interposed between frame and ground which eliminates any danger of arcs being formed between frame and positive bus bar by accident. A very serious menace to the lives of workmen is thus removed, and although there still is the possibility of electric shock, severe injury in this way is not likely to occur if reasonable care is used. To prevent shocks an insulating platform may be built around the board and near-by metallic bodies insulated or inclosed by insulating material.

It may be added that in those types of switchboards where bus bars are out of reach of persons and too far apart, and too far from the frame to allow short-circuiting by tools there is no objection to grounding.

(*d*) Interior Fixtures.—An important class of metallic bodies inclosing electrical circuits is that which includes the metallic inclosing shells of interior electric fixtures, such as the shells of lamp sockets and chandeliers. More persons come in contact with these than with any other form of electrical equipment, and it is, therefore, exceedingly necessary that they be made safe by grounding through as low a resistance as it is practicable to obtain. Otherwise they may become dangerous on account of accidental grounds forming within them which puts them at the potential above ground of the circuit which they inclose. Or, if accidental contact occurs between the low-voltage circuit and a high-voltage circuit, arcing discharges to the shell may occur, making it very dangerous to approach, especially in damp places.

In grounding these shells it is well to observe certain precautions: First, in every case separate ground wires should be provided—that is, fixtures should not be connected to the ground wire of a circuit or a lightning arrester, for, if they are, in the case of a current or lightning discharge passing over the ground wire, a high potential may be impressed upon the fixture due to the impedance of the ground wire and the resistance of the ground connection. Second, in no case should a fixture be connected to a grounded wire of a circuit, because in the event of an accidental contact between the low-voltage circuit and a high-voltage line, the grounded conductor of the circuit is liable to a potential rise above ground, due to the resistance of the ground connection, which may not be dangerous when impressed only upon the circuit itself, but which, when impressed upon the fixture, may be

a menace to life. Finally, grounding of fixtures is important everywhere, but is especially so in damp places and in places within reach either by hand or foot of grounded metal, such as water and gas pipes and steel building frames.

As a special precaution in basements, bathrooms, refrigerating rooms, or places of any kind where damp processes are carried on, porcelain or weatherproof sockets may be installed. In so far as these can be made use of, they obviate the necessity for grounding, but it is not practicable to do away with metal entirely, so a certain amount of grounding is usually necessary. In some places, as set forth below, grounding is relatively a simple matter because near-by metal can be used, but in others a long separate ground wire may be required. To this, however, any number of fixtures may be attached if it is desirable to do so.

(*e*) Grounding in Large Buildings.—A matter which should be mentioned is that to obtain the effect of grounding does not in every case require connection to the earth itself. In a large building, for instance, which contains electric circuits in conduit, water and gas piping, structural metal, and other metallic bodies, it is in some cases desirable to isolate from earth all of the metal within the buildings to prevent electrolysis by stray currents from outside. To this end, it may be advisable to put insulating joints in water and gas pipes were they enter the building. As a rule, the metal work is then interconnected electrically and allowed to remain isolated from earth. Conduit, transformer cases, fixtures, or other conducting bodies may be considered as made sufficiently safe if they are connected to such an interconnected mass of metal. No difference of potential can then exist between them and surrounding conducting objects which will be dangerous to life. It is as necessary as before, however, that devices for detecting accidental grounds be installed in the building, using the interconnected metal as earth. It should also be emphasized that under no conditions should an accidental ground be allowed long to exist, because of the dangers already discussed and the further danger in some cases of electrolysis. As before stated, if an accidental ground is allowed long to exist, there is, in addition to danger from electrolysis, a certain degree of danger to life and also of fire, even though the most elaborate precautions as regards grounding are taken.

In conclusion it may be stated that to ground electrical circuits to the electrically isolated metal work of buildings is objectionable

in that there is a possibility, in some cases, of damage by electrolysis, and in others, that the metal work may attain a high potential against ground due to the entrance of high voltage from primary distribution lines or arc circuits with a consequent danger to life and property. In grounding electrical circuits connections, therefore, should be made either outside of buildings, or if within buildings, to metallically continuous structures extending into the earth at or near the point where the electrical circuit enters.[15]

6. HIGH-VOLTAGE TRANSMISSION AND DISTRIBUTION SYSTEMS

The use of permanent ground connections in high-voltage transmission and distribution systems is limited largely to grounding the neutrals of 3-phase, 3-wire, and 3-phase, 4-wire circuits for the purpose of averting electrical dangers to lines and plant equipment and in that way improving operating conditions. Grounding for this purpose is by no means general, however, and there are many adverse opinions as to its use in any case. The chief danger averted in this way is that due to accidental grounds which may lead to destructive oscillations or short circuits, underground cables being more susceptible to damage from these causes than aerial lines. By grounding the neutral, such accidental grounds can be turned into short circuits on one phase as soon as they are formed, and through the operation of circuit breakers, automatically cut out the faulty cables before the grounds develop into short circuits between phases. In general, the cable will then be left in such a condition that by means of well-known methods for locating accidental grounds, the approximate location of the fault is possible; whereas, if the accidental ground is allowed to develop into a short circuit between phases, such location is practically impossible, except by sectionalizing the cable at manholes and testing each section by itself. This method of protection is used in many underground systems, although it has certain disadvantages, and is used to a less extent in aerial lines. The chief disadvantage is that an accidental ground on one phase of a line immediately cuts that line out of circuit; whereas, in the interest of continuous service, it is in many instances desirable to operate a line temporarily, even though one phase is accidentally grounded.

In that case the resistance of the ground connection must be such as to allow a sufficient flow of current to trip the circuit

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[15] See rules 95 *a* and *b*, Appendix II, N. E. S. C.

breaker having the highest current setting of any in the system, and still not put a heavier strain on the generating equipment than is absolutely necessary. The total resistance required will, therefore, depend upon the current-carrying capacity of the largest feeder and the voltage at which the system is operated. Furthermore, this resistance must not be fluctuating to any great degree. In the past, the desirability of limiting the current flow has been recognized, but in many instances the ground connection has been assumed to be of zero resistance, and in order to limit the current flow, rheostats have been placed between the neutral point and earth, the impedance of the rheostats being calculated without regard to the resistance of the ground connection. In the event of an accidental ground, it was found, of course, that the current flow was less than was expected.

In nearly all modern systems, the resistance required between neutral and earth is such that the resistance of the ground connection need be but a small part of the total, but it must always be taken into account. Rheostats may, therefore, be placed in the neutral connection, and in that way not only can the current be limited to the proper value, but fluctuations of the total resistance minimized; that is, in comparison with what they would be if the ground connection itself were depended upon to furnish all of the current-limiting resistance. Heretofore, the rheostats used in some large 13 000 to 20 000-volt systems ranged from 6 to 20 ohms, so a ground connection of 1-ohm resistance or less should give satisfactory results in such cases. The energy absorbing capacity of the ground connection need not be great unless it is planned to use the earth as a conductor if one phase is disabled. In that event the ground connection must be able to carry the full load current of one phase continuously without an appreciable change in resistance. Ordinarily, however, where the ground connection is supposed to carry current only for a sufficient length of time to trip a circuit breaker, the energy absorbing capacity is of little importance, since, though the currents carried are large, they flow for only a short time.

Grounding the neutral is also used in connection with 3-phase, 4-wire distribution systems for the purpose of preventing undesirable fluctuations of voltage in low-voltage circuits and differences of potential between the neutral wire and ground. As long as the insulation resistance of each wire to ground is the same, there is, of course, no necessity for grounding; but this is rarely

the case, at least for any length of time, and to guard against the unbalancing effects of accidental grounds of high resistance it is necessary to ground the neutral wire. The resistance required of the ground connection in this case depends upon the extent of the system, the voltage, and other factors. In general, it may be said that the current carried by such a ground connection will be of but a few amperes in strength; that is, of the same order of magnitude at the charging current of the line. The ground connection should be such as to carry this current for considerable lengths of time without change of resistance or a voltage drop appreciable in comparison with the voltage of the system. If the ground connection is expected to serve two purposes, namely, that of eliminating the unbalancing effects due to leaks, and also of cutting out faulty lines when accidental grounds of low resistance develop, it will almost always be found that if the resistance of the ground connection is suited to the latter purpose, the first will be more than amply served.

7. ELECTRICAL SYSTEMS UNDER CONSTRUCTION OR REPAIR

Electrical systems under construction or repair should, when possible, be disconnected from the source of energy and grounded temporarily for the protection of workmen employed upon them. In general, workmen are liable to electrical dangers from three sources when so engaged: First, the line on which they are working may be switched in by mistake; second, danger may arise from atmospheric electrical disturbances; third, there may be danger through leakage or induction from other lines. With regard to the first, it is best guarded against by suitable operating precautions such as locking and labeling switches; and further, by short-circuiting the line at the point where the work is being done. In addition to these precautions most companies require that the line be grounded, if there is even a slight possibility that danger is likely to proceed from the second and third sources named above.

(*a*) Danger to Workmen from Atmospheric Electricity.—There is a very real danger from atmospheric electric disturbances which may set up large differences of potential between line and ground, especially in long aerial lines. In underground lines such disturbances are in most cases of little moment unless part of the line is overhead and the rest underground, in which case atmospheric electric disturbances originating in the aerial portion of the

line may, in a measure, affect the underground portion. In aerial lines the greatest danger comes from lightning striking the lines directly, the effects of which may be carried many miles with sufficient force to kill a person. This extreme danger is likely to arise, of course, only during the lightning season; but aside from this, it is necessary at all times of the year to guard against the effects of accumulated or induced charges. Grounding the line is the most effective remedy and is to be regarded as important in any case, and especially so during the lightning season. Complete protection, of course, is not obtainable, for, even though the line is grounded at short intervals, through a low resistance, a near-by lightning stroke is extremely dangerous. Therefore, when thunderstorms are in the immediate vicinity of the line it is desirable to suspend work until the danger is past, or at least until greatly lessened. This is especially the case with workmen on the ground handling wires which are connected to the line. Workmen on poles, on the other hand, are not in as great danger as those on the ground, and the same may be said of workmen on steel towers, if the line wires are electrically connected to the towers.

In grounding lines to avert danger from atmospheric electric disturbances, the inability to provide complete protection mentioned in the preceding paragraph is due to the fact that a large part of such disturbances either originate or end in high-frequency effects. With such high-frequency effects large differences of potential may exist between parts of the line and ground in spite of all the grounding that is practicable. On the other hand, grounding to relieve steady electrostatic stress between line and ground in a successful manner is readily done, and moreover the resistance of ground connections for this purpose is not an important matter. Ground connections at intervals of a few thousand feet, the resistance of such connections being 20 ohms or so each, will be found sufficient protection against accumulated charges. Such ground connections may in a measure also protect against high-frequency effects set up by direct strokes of lightning. In fact, as stated above, it is doubtful if any practicable amount of grounding would be sufficient to give complete protection against direct strokes of lightning, even though the strokes be several miles away from the place where work is being done. The best procedure, therefore, seems to be that of grounding the line to protect against accumulated charges, and in the event of severe

lightning disturbances in the immediate vicinity, to keep away from the line until the disturbance ceases.

(*b*) Danger Through Leakage from Neighboring Lines.—Danger from leakage and induction from other lines is present, of course, only where lines of sufficient voltage to be dangerous to human life are near the line under construction or repair. If there is such proximity between lines, it must, in all cases, be considered as a source of danger and the maximum degree of danger provided against. The maximum degree of danger arises when a direct contact occurs between the lines in a manner similar to that illustrated in Fig. 4 for the case of low-voltage transformer windings. In the event of such a contact between the lines, the only definite limit to current flow is that set by the protective devices in the live line with which contact is made. The resistance of the ground connection must, therefore, be such as to allow a sufficient current to flow to operate these protective devices without a rise of potential between the protected line and ground that would be great enough to be dangerous to human life. As mentioned heretofore, 150 volts is considered as the maximum voltage to which persons can be subjected with safety. The maximum allowable resistance of the ground connection can, therefore, be expressed by $R = \frac{150}{\text{Current}}$, where the current is that required to operate the fuses or circuit breakers which protect the live wire from overload. This appears to give a very low resistance for such ground connections, especially where circuits of large current capacity are to be guarded against, but nothing greater than the result given by this formula can be considered as giving a "sufficient ground connection" as defined by most safety rules. To provide such ground connections will, however, rarely work a hardship. The need for them appears principally in urban districts where underground metal structures of great extent are plentiful and easy of access. Moreover, in plants and substations permanent connections can be made with terminals provided for convenient attachment, while in other places connections can be made to water pipes as occasion requires. On isolated rural lines the grounding required will rarely exceed that described in the preceding paragraph.

When lines are grounded temporarily, it is very desirable that the electrical characteristics of the ground connections used be known; in fact, it is almost as desirable as where permanent grounds

are made. This is always possible in the case of grounds made at stations, for here the safety arrangements are more or less constantly in use and can be made permanent, the resistance being checked periodically. In the field, however, it is not always practicable to make measurements, and it may be necessary to rely upon inspection only. To one familiar with soil conditions in a particular locality this may be sufficient, but in general, reliance should be placed on unmeasured ground connections only in emergencies, or in cases where it is very evident that severe conditions will not be met by the safety arrangements. In every case measurements with ammeter and voltmeter or Kohlrausch bridge should be made if practicable.

In making ground connections such as those just described, there is an incentive to use hasty methods, but for the sake of safety it is wise to make such connections secure. Clamps may be considered sufficiently secure if they are of sturdy construction. The ground wire should be of the same size as the line wire to which it is attached, and bolted or soldered to the clamps, one of which should be a spring clamp for attaching to the line. In grounding the line the ground wire should first be clamped to the water pipe or other conductor which serves as the ground connection. Then with a switch hook the spring clamp may be sprung over the line wire, which obviates the necessity for touching the line in any way while there is a possibility that it may be dangerous.

8. LIGHTNING ARRESTERS AND OVERHEAD GROUND WIRES

Since lightning arresters and overhead ground wires protect life only indirectly and are designed almost solely for the purpose of protecting plant equipment and lines from lightning and overvoltages, the discussion herein given to ground connections for them will be brief and devoted largely to pointing out the dangers that may arise from the improper use of such ground connections.

(*a*) Danger from Improper Use of a Ground Connection for a Lightning Arrester.—The chief danger which may arise is brought about by connecting to the ground wire of the lightning arrester those metallic bodies which it is desirable to ground to promote personal safety. These bodies include transformer cases, machine frames, low-voltage circuits, and others. Regarded only from the standpoint of strain on insulation between electrical circuits and ground or between high-voltage and low-voltage circuits, due to lightning or other disturbances, there is a distinct

advantage in thus connecting to the ground wire of the lightning arrester, because in that case the strain on the insulation is limited to that accompanying the drop in voltage across the arrester while it is discharging; and by proper design of the arrester, this strain can be made comparable with the strain on insulation under normal conditions of operation, excepting, of course, those cases in which there is a marked effect from the time lag in the discharge of the arrester. As a consequence, the use of the lightning arrester ground connection for the purpose of grounding transformer cases, low-voltage circuits, and the like, has been many times recommended and is now practiced by many companies.

The greatest objection to it, however, is this: In many cases the resistance of the ground connection is high, and in fact, in all cases there is some resistance in the ground connection. Moreover, it may take a long wire to reach from the ground end of the arrester to the point where actual contact with the earth occurs, especially if the soil near the arrester is not suitable for making ground connections, so the high-frequence impedance in the ground wire may be considerable. Now, the rate of discharge over an arrester may be very great. In fact, some of the recent designs of lightning arresters for distribution circuits place the maximum discharge rate of the arrester at 650 amperes,[16] experience having shown that it is unsafe to assume a lower maximum discharge rate than this. Hence, in the event of a severe lightning stroke passing over the arrester, the potential between the ground end of the arrester and earth may be hundreds, or even thousands, of volts, this voltage to ground being imparted to whatever metallic bodies are connected to the ground wire at that point. Obviously, a person in contact with one of the metallic bodies at the time of the stroke would be likely to receive a severe shock, and there would also be a likelihood of sparks from them to ground which might be dangerous in some cases.

It is desirable, therefore, to give the lightning arrester a separate ground connection[17] in every case if it is possible and connect transformer cases and other metallic bodies to the arrester ground wire only when they are inaccessible to persons. This will be found to be the case in some instances, but where persons can come in contact with the grounded metal, such interconnection should be avoided carefully. The same is true of earth connections for overhead ground wires.

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[16] Creighton and Shavor, Trans. A. I. E. E., 31, p. 811; 1912. [17] See rule 97*a*, Appendix II, N. E. S. C.

A word may be said here with regard to low-voltage alternating-current circuits. It has been recommended by some that the cores and cases of the transformers feeding such circuits be connected to the earth wire of the lightning arrester and a short spark gap placed between the earth wire and the middle wire of the low-voltage circuit. This spark gap is supposed to break down and relieve any high potential difference between low-voltage circuit and ground. A gap of this kind may be efficacious under certain conditions, but in the event of a lightning discharge across the arrester, it would offer no protection to persons who at the time were in contact with the low-voltage circuit. As a matter of fact, the spark gap would break down and a part of the lightning discharge tend to go to ground through the person's body. Such spark gaps should, therefore, be excluded unless there is no danger to persons, or probability of fire, if a high-potential should exist between the low-voltage circuit and ground. To gain the maximum degree of protection, the middle wire must be solidly grounded, as pointed out in this paper, and that separately from the ground connection for the lightning arrester. It may appear that to be obliged to install two ground connections at a single installation would work a hardship, yet in many cases personal safety demands it. It should be mentioned, however, that there is no objection to grounding a lightning arrester and a low-voltage circuit or a metallic body to a water system at points near each other, unless the resistance of the water-pipe ground connection is extraordinarily high, or the main is reached only through a long service pipe. In the latter case a separate ground connection for the arresters would be advisable.[18]

(*b*) Effect of Resistance in the Ground Connection.—The actual resistance allowable in a ground connection for a lightning arrester depends to some extent upon the character of the equipment it is intended to protect. Moreover, this resistance is important only in so far as it is a factor in increasing the impedance in the path of the lightning discharge through the arrester to ground. In general, it should be made as low as practicable for the following reason: When a discharge takes place over an arrester, the impedance offered to the discharge to ground should be as small as it can be made in order to relieve the line of strain as quickly as possible. It is only after the initial discharge has occurred that a high resistance in the arrester circuit is desirable

[18] See Rule 97*b*, Appendix II.

for the purpose of preventing an arc being formed by the line current. Various devices are used to produce a sudden increase of resistance of the arrester circuit, most of which make use of the line current following the initial discharge to produce the desired result. Among these may be named the electrolytic lightning arrester. The multigap arrester makes use of the cooling properties of the arc vapors of certain metals. Both of these are quite efficacious in increasing the resistance of the arrester circuit enormously during the passage of the line current after the lightning discharge for the time of a half cycle, or two or three cycles at most. In this case, therefore, resistance in the ground connection only works to interfere with the effective operation of the arrester and should be reduced to the lowest practicable limit.

On the other hand, arresters protecting circuits which carry currents at low voltage, such as telephone and telegraph lines, seem in practice to operate more or less satisfactorily with considerable resistance in the ground connection. Ground connections in these circuits of 40 or 50 or even several hundred ohms resistance are not uncommon. Their effectiveness, however, is probably due to the prevalence of mild lightning discharges on such lines. Moreover, as a rule, there are a large number of such circuits on each pole line and many arresters on each circuit, so that a lightning stroke may often be divided and carried off through a number of arresters in parallel. Nevertheless, heavy discharges are likely to cause severe damage. The only advantage of resistance in the ground connection in any case is that it tends to damp out oscillations in the arrester circuit. The lowest resistance readily obtainable in practice may be considered sufficient for this, however, and the greater the resistance the greater the disadvantages in other directions.

9. LIGHTNING RODS

The ground connection is the most vital part of a lightning rod system. If it is poor, the effectiveness of the system is greatly diminished. Moreover, the conditions under which a ground connection for a lightning rod must operate are severe. In the first place, inspection is usually lax, there being no responsible utility concerned, and the average owner seems to think that a lightning rod should remain operative without attention as long as the average building lasts. The cause of this inattention is probably to be found in the fact that a lightning rod is

called upon to operate only infrequently. As a consequence, unless specific arrangements are made for periodical inspection, it is likely that inspection will be omitted entirely, or at most be made very irregularly and inadequately. Therefore, in order that assurance may be had that rods will be in good condition when their services are required, it is necessary for persons installing them to provide ground connections that will successfully withstand corrosion and which are well protected from mechanical injury. In the second place, the currents and potential differences involved in lightning strokes are enormous. The maximum current may, in some cases, be as much as 25 000 amperes,[19] and furthermore, the steepness of the wave front of the flash may be the equivalent of hundreds of thousands of cycles per second. Consequently, in the event of a stroke, high potials may be set up between the lightning rod and ground, sufficient in many cases to break down large air gaps. The magnitude of these potentials may be estimated by simply multiplying the assumed maximum current of a lightning stroke by the resistance of the ground connection. Ordinarily, ground connections for lightning rods, as now installed, have a resistance of many ohms, 10 ohms being a rather low value which may be assumed for calculation. Since, as pointed out above, the maximum current of a lightning flash may be as much as 25 000 amperes, it is readily seen that the potential between rod and ground when a stroke is passing may reach a value of 250 000 volts. This does not include, of course, the component of the voltage taken up by the inductance of the rod, which may be greater or less than that taken up by the resistance of the ground connection. Hence, it is obvious that extremely dangerous potential differences may exist instantaneously between rod and ground.

In the installation of lightning rods, therefore, great care has to be exercised to obtain maximum practicable effectiveness. Long life of all parts of the system must be assured, and the rods and ground connections must be disposed to the best advantage. Since the inductance of a divided circuit is less than that of a single circuit, it is desirable to have the system come to earth at a number of places as far removed from each other as the contour of the object to be protected will readily allow. Moreover,

[19] Pockels, Annalen Phys. Chem., 63, p. 195; Annalen Phys. Chem., 65, pt. 2, p. 458; Phys. Zeit., 2, p. 306.

the greater the number of such grounds, the better, having regard, of course, to the economical use of material. In no case should there be less than two points of connection with the earth, unless the object to be protected is a tree or a flagpole; in these cases a single ground connection is all that is practicable. The multiplicity of down conductors minimizes the inductance of the system, while that of the ground connections minimizes the resistance. It may also be stated that a number of ground connections in parallel at a distance from each other, even though each is of high resistance, is better than a single ground connection of low resistance. The total resistance to earth should in any case be made as low as practicable.

In making a ground connection for a lightning rod, it is necessary to make contact with the stratum of permanently moist earth nearest the surface of the ground. Ground connections in wells or other places where the actual contact with the earth occurs only at considerable distances below this stratum are not to be relied upon for protection for the following reason: If conditions exist for a lightning discharge between cloud and earth, the charge on the earth induced by the cloud charge resides at the surface of the ground if it is moist, or if it is not, then at the surface of the uppermost stratum of moist earth. This is in accordance with experimental knowledge of electricity; that is, the effects of an electric charge are not manifested beneath the surface of a conductor. Moreover, that this is the case with lightning charges is indicated by the fact that a lightning discharge to earth where the surface is damp leaves scarcely any marks; whereas in desert regions, or very dry places, fulgurites are formed or the ground is torn up, showing that the lightning stroke has penetrated the ground. In making ground connections for lightning rods, therefore, contact with the uppermost stratum of moist earth is absolutely essential to the safe operation of the system, for when the discharge occurs, the charge on the surface of the ground will tend to rush into the rod, and this will occur by the most direct path. If the ground connection makes contact much below the uppermost stratum of moist earth, the discharge will leap to the rod at the surface of the ground instead of traveling downward to where contact is made with the earth and then back again.

As an example, the Washington Monument in the District of Columbia may be cited. When the first lightning rod equipment was put on the Monument, a ground connection was made by dig-

ging a well 33 feet in depth below the bottom of the drum pit, and 15 feet 8 inches below the bottom of the masonry foundation. The water stands in this well permanently 2 feet 8 inches above its bottom. Three-fourths inch, soft copper rods led to the bottom of the well, which was filled to the masonry mentioned above with sand. The measured resistance of this earth connection was 2.2 ohms.[20] On several occasions lightning struck the Monument and followed the conductors provided for it to the bottom of the shaft, where it jumped to a plate in the floor, passing into the engine room and other places and doing considerable damage. Later a connection was made from the conductors in the bottom of the shaft to a water pipe in the motor room, with the result that a later stroke passed to earth with but slight damage and did not leave the conductors at any point. No further trouble has been experienced.

As pointed out above, the resistance and inductance of the system should be made as low as practicable. At first sight it might seem that too low a resistance could be obtained; that is, if the resistance were negligible, destructive oscillations in the rod might result from the impulse given by the lightning stroke. In practice, however, the chance of obtaining an effect of this kind through too little resistance in the ground connection need not be taken into consideration. On the contrary, the real difficulty in nearly all cases is that of getting a sufficiently low resistance.

10. METER SYSTEMS, SIGNAL SYSTEMS, AND AUXILIARY GROUND CONNECTIONS FOR TESTING PURPOSES

The use of ground connections for meter systems on high voltage lines is confined chiefly to preventing a rise of potential against ground of the meter circuits which may endanger the lives of attendants or injure the insulation. Such a rise of potential may occur either through electrostatic induction, or through failure of insulation in instrument transformers which permits the line voltage and current to enter the meter circuits. To guard against the first is not difficult. A ground connection of even rather high resistance, say several hundred ohms, will serve the purpose. To guard against the second, however, is not so easy. Here a low resistance of the ground connection is required, because in the event of a failure of insulation, there may be a heavy flow of current to earth. Connection to water pipes is especially to be recommended.

[20] Reports of Engineer Officers in Charge of Public Buildings and Grounds in Washington: 1885 to 1912.

Earth connections for signal systems often form part of the operating circuit, and for that reason special attention needs to be given to their resistance, more particularly, to the variation of the resistance with seasons. A signal system installed in summer might work in a satisfactory manner, but with freezing weather an increase of resistance of the ground connections would take place, possibly enough to render the system inoperative. In making the installation, therefore, care should be taken to allow for seasonal changes.

Auxiliary ground connections are frequently needed for testing purposes. The resistance and other electrical characteristics are here determined by the requirements of each case. In testing insulation, for example, the resistance of the ground connection may be very high—several thousand ohms need not be considered too high for good results—but for other purposes it may need to be low. A case in point is testing for the energy-absorbing capacity of ground connections for electrical circuits, which is taken up later under Section VI, "Inspection and Testing."

IV. DIFFERENT FORMS OF GROUND CONNECTIONS AND THE ELECTRICAL CHARACTERISTICS OF EACH

The different types of ground connections in common use may be enumerated as follows: (1) Driven pipes, (2) plates, (3) strips, (4) patented devices, and (5) water pipes. The electrical characteristics of each type and the extent of its suitability for grounding electrical systems are discussed below, patented devices being included under one head because, although there are many of them on the market, they are not fundamentally different from one another. Some space is also devoted to multiple ground connections.

1. DRIVEN PIPES

For many purposes driven pipes are economical and reasonably satisfactory, especially if the soil is deep and not so stony as to prevent driving them. They serve very well for lightning rods, lightning arresters, low-voltage circuits fed by transformers of small power rating where there is little likelihood of contact between high-voltage and low-voltage wires, and for other electrical circuits and apparatus which do not require a resistance to flow of current into the earth of less than a few ohms. Where very low resistances are required, however, they are, in general, not satis-

factory. Nevertheless, as compared with other types of grounds, they possess a marked advantage in that connection between pipe and ground wire can be made above the surface of the soil, enabling easy inspection; and they are renewable at relatively low cost. Moreover, the ground area required for an earth connection of this type is small, making for convenience in some places where excavation is out of the question because of restricted space, or pavements.

(*a*) VARIATION OF RESISTANCE WITH DEPTH.—This characteristic of driven pipes has been investigated heretofore by Creighton.[21] His results have been checked in this investigation, using 54 specimens of three-fourth inch galvanized iron pipe of lengths varying in steps of 1 foot up to 10 feet. These were driven in rather stony clay soil. Table 1 gives the number of specimens and the average of their measured resistances for each length. The measurements were made by means of the ammeter-voltmeter method, with alternating current at 60 cycles per second. A detailed description of this method is given further on in this paper under "Testing" in Section VI, 2 (*a*), (*b*), and (*c*). When the pipes were driven, the ground was very wet, and when the data given in Table 1 were obtained, they had been in place seven months, so there was ample opportunity for the soil to settle and eliminate disturbances due to driving. The values of resistance, however, are to be considered as having probable errors of 2 or 3 per cent because of fluctuations of voltage while readings were taken, which were due to varying loads on the line at other points.

TABLE 1.—Variation of Resistance of Driven Pipes with Depth[a]

Specimens	Depth in feet	$2l=L$ in centimeters	Capacity in electrostatic units	Average measured resistance	Calculated resistance, uniform soil
				Ohms	Ohms
8	1	61.0	7.92	167	149.3
8	2	122.0	13.45	76.3	87.8
8	3	183.0	18.52	47.2	63.8
8	4	244.0	23.35	37.5	50.6
8	5	304.0	28.00	49.5	42.3
1	6	366.0	32.40	42.5	36.5
3	7	427.0	36.85	31.0	32.1
1	8	488.0	41.20	22.5	28.7
1	9	549.0	45.40	23.5	26.0
8	10	610.0	49.60	36.5	23.8

[a] External diameter of pipes used in this test, 1.02 inches. $\rho=7420$ ohms per cubic centimeter.

[21] General Electric Review, 15, pp. 15 and 66.

Referring to Table 1 it will be seen that the results of the measurements are very irregular; for instance, the average resistance to flow of current away from a group of pipes driven 10 feet into the ground is practically the same as for a group driven 4 feet. The resistances to flow of current away from individual specimens were also found to be very irregular, and in all cases the irregularities were much greater than those which could be attributed to errors in measurement. The soil, however, was found to be very nonhomogeneous, and it is undoubtedly to this that the larger part of the irregularities must be attributed. In fact, in driving it was discovered that the greater lengths of pipe penetrated a stratum which consisted of nearly all small bowlders of 2 to 5 inches in diameter. The resistivity of such bowlders is extremely high in comparison with that of soil and their presence tends to produce differences in resistances between specimens of the same kind on account of their nonuniform distribution. Because of these irregularities it would be more or less misleading to attempt to show the relation between resistance and depth by drawing a curve through the points representing the observed values, so a curve was constructed the shape of which would at least approximate that obtained by making observations on pipes driven in soil of uniform resistivity.

In constructing this curve use was made of the formula $R=\frac{\rho}{2\pi C}$, which was given under resistance of ground connections. In this formula R is the resistance to flow of current away from a ground connection, ρ the resistivity of the soil, and C the combined electrostatic capacity in free space of the electrode and its image above the surface of the ground, the surface of the ground being supposed in this case to lie in a plane at right angles to the axis of the pipe. There seems to be no available formula for the electrostatic capacity of a cylinder in free space, so in calculating C an approximation was made by using the formula for the capacity of an ellipsoid of revolution, assuming the axes of the ellipsoid to be equal to the length and external diameter, respectively, of the pipe. This formula, for an ellipsoid of revolution of which the length of the major axis is great in comparison with that of the minor axis, is $C=\frac{L}{2\log\frac{2L}{d}}$, where L is the length of the major axis and d of the minor axis.

The image of a driven pipe above the surface of the ground would be another pipe of the same length l and external diameter d extending above the surface. The value of L is therefore equal to $2l$, since C refers to the combination of electrode and image. The ratio of major to minor axis for the lengths of pipe under consideration ranges from 24 to 240. Just what error arises from the use of this formula can not, of course, be told. Because of the method of cutting and driving, however, a pipe can be considered as a cylinder with rounded corners. Hence, it does not seem that the difference in capacity between a pipe of given length and diameter and an ellipsoid of revolution of which the major and minor axes corresponded, respectively, to the length and diameter of the pipe would be more than a few per cent. At any rate the method can be considered as a rough approximation and is the most convenient means at hand for smoothing out irregularities in the observations.

From the foregoing formula C has been calculated for the various lengths of pipe, the results being given in Table 1. Substituting in $\rho = 2\pi\ C\ R$, the value of ρ corresponding to each set of measurements is found. The average value of ρ for the 10 sets of measurements is 7420 ohms per cm ^{3}, from which in turn has been calculated the resistance for each length of pipe as if the resistivity of the soil were uniform. These results are given in the last column of Table 1 and have been used to plot the curve in Fig. 11. The circles show where the points corresponding to the measured resistances fall and are about evenly distributed on either side of the curve. As stated above, this curve can be considered as only a rough approximation to the true curve, but nevertheless shows clearly how the resistance to flow of current away from a pipe driven in soil of uniform resistivity varies with the depth. Evidently not much is to be gained by driving pipes more than 10 feet after moist earth has been reached. As will be shown later, it is, in most cases, more economical to decrease the resistance by putting pipes in parallel than by driving deeper than 10 feet into conducting earth.

Since R depends directly upon ρ, the shape of the curve will be the same no matter what the resistivity may be; that is, if ρ_1 represents the resistivity corresponding to a given curve, and ρ_2 the resistivity corresponding to any other curve, the latter curve may be found by multiplying the ordinates of the given curve by $\frac{\rho_2}{\rho_1}$,

if the sizes and lengths of pipe concerned are the same in the two cases. Practically, however, the curve shows only what depth in conducting earth it is most desirable to attain with driven pipes.

(*b*) VARIATION OF RESISTANCE BETWEEN TWO DRIVEN PIPES WITH DEPTH AND DISTANCE APART.—For this experiment 40 specimens were used. As indicated in Table 2, where the results of the measurements are given, their lengths ranged from 2 to 10 feet and their distances apart from 6 inches to 25 feet. They were driven in the soil as described in the preceding section, the specimens in

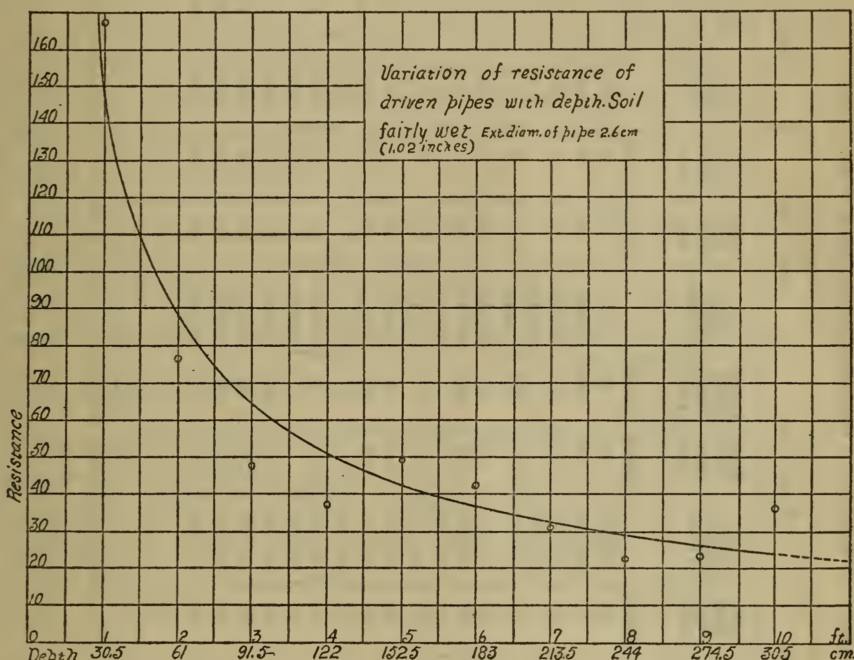

FIG. 11

the two cases, with certain exceptions, being, in fact, identical. The measurements were made by the ammeter voltmeter method. As stated heretofore, this method is described under "Testing" in Section VI, 2 (*a*), (*b*), and (*c*).

In this case, of course, irregularities in the results due to the non-homogeneity of the soil are present the same as in the preceding experiment. In order to draw a curve which will give a clear idea of the way in which the resistance to flow of current from one pipe to another varies with the distance between them, it is therefore necessary to eliminate these irregularities. As previously shown, it is possible to calculate from $R = \frac{\rho}{2\pi C}$ the

TABLE 2.—Variation of Resistance Between Driven Pipes With Distance Apart [a]

Resistance of each specimen				Distance apart	Depth, 2 feet			Depth, 3 feet			Depth, 4 feet			Depth, 5 feet			Depth, 10 feet		
No.	Resistance	No.	Resistance		Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance	Specimens in series	Measured resistance	Calculated resistance
	Ohms		Ohms	Feet		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms
66	127	99	54	0.5	75–76	164	161	112–113	96	84	105–106	59	59	82–83	74	76	98–99	52	54
67	57	100	51	1	76–77	187	185	113–114	110	101	106–107	84	77	83–84	93	87	99–100	64	69
68	44	101	59	2	77–78	216	214	114–115	120	117	107–108	99	91	84–85	131	118	100–101	74	76
69	62	102	65	3	78–79	217	221	115–116	127	125	106–108	98	94	83–85	139	124	99–101	90	86
74	42	103	65	3	76–78			113–115			108–109			85–86			101–102		
75	125	104	61	4	79–80	224	225	116–117	126	129	109–110	100	98	86–87	144	133	102–103	104	90
76	125	105	60	5	77–79	215	229	114–116	134	134	107–109	118	105	84–86	157	135	100–102	96	94
77	123	106	61	6	80–81	227	232	117–118	137	136	106–109	106	104	83–86	131	132	99–102	105	96
78	125	107	70	6	76–79			113–116			110–111			87–88			103–104		
79	108	108	61	7	78–80	255	239	115–117	137	137	108–110	104	105	85–87	141	136	101–103	109	99
80	137	109	65	9	77–80	256	242	114–117	145	140	107–110	117	110	84–87	144	140	100–103	104	101
81	110	110	58	10	81–66			118–67			111–68			88–69			104–74		
82	69	111	59	10	79–81	231	238	116–118	134	141	109–111	105	108	86–88	129	137	102–104	105	102
83	76	112	88	10	76–80			113–117			106–110			83–87			99–103		
84	82	113	84	13	78–81	231	242	115–118	140	143	108–111	111	110	85–88	134	140	101–104	112	105
85	83	114	80	15	77–81	231	243	114–118	146	145	107–111	121	111	84–88	136	143	100–104	104	105
86	90	115	75	20	79–66	231	243	116–67	123	144	109–68	103	113	86–69	148	144	102–74	102	108
87	71	116	71	25	77–66	252	248	114–67	132	145	107–68	110	115	84–69	141	145	100–74	89	108
88	59	117	76	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
98	54	118	72	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......

[a] Where more than one pair of electrodes were available at any given distance apart, average results were used in tabulation and in plotting curves.

resistance to flow of current from one electrode to another if ρ and C are known, ρ being the resistivity of the soil and C the electrostatic capacity of the condenser formed by one of the electrodes and its image above the surface of the ground, on the one hand, and the other electrode and its image on the other hand. If C were known for the different lengths of pipe and their distances apart, an average value of ρ could be obtained, from which, in turn, could be calculated the different values of R as if the resistivity of the soil were uniform throughout. At present there seems, however, to be no available formula for calculating the value of C in the case of pipes, so it was necessary to resort to a less desirable means of eliminating irregularities, a method which, in fact, eliminates irregularities with a fair degree of approximation between measurements on pipes of the same length, but not between groups of different lengths.

As previously indicated, the resistance to flow of current from one electrode to another, as well as away from a single electrode, depends directly upon the resistivity of the soil. Suppose that R_1, R_2, $R_3 \cdots R_n$ are the measured resistances to flow of current away from each pipe of a group of the same length driven at different distances from each other. Then $R_{av} = \frac{R_1 + R_2 + R_3 + \cdots R_n}{n}$ is the resistance which each would have if the resistivity of the soil were everywhere equal to ρ_{av}. Let R' be the measured resistance to flow of current from any one of the driven pipes to another, say from (1) to (2); R' will correspond to a resistivity of the soil everywhere equal to ρ'. In order to reduce R' to a value R which it would have if the resistivity of the soil were everywhere equal to ρ_{av}, it is only necessary to put $R = \frac{\rho_{av.}}{\rho'} R'$. The value of ρ' must be determined, however, before use can be made of the formula. If the pipes are at an infinite distance from each other, it is evident that $\rho' = \frac{\rho_1 + \rho_2}{2}$ where ρ_1 and ρ_2 are the values of resistivity corresponding to R_1 and R_2. Then $R = \frac{2\,\rho_{av}}{\rho_1 + \rho_2} R' = \frac{2R_{av}}{R_1 + R_2} R'$, since $\frac{2\,\rho_{av}}{\rho_1 + \rho_2} = \frac{2R_{av}}{R_1 + R_2}$. This holds exactly for pipes driven at a great distance from each other, but when they are brought close together the formula is only an approximation. However, because of the fact that it is the soil in the immediate vicinity of the electrode which has the greatest effect in producing resistance, the error becomes appreciable only when the electrodes are very near each other.

The results of Table 2 have been reduced in accordance with this formula, and curves corresponding to groups of pipes 2 feet, 5 feet, and 10 feet lengths are shown in Fig. 12. The circles and dots represent the observed values of resistance and seem more or less evenly distributed on either side of their respective curves. As the distance between the pipes increases the ordinate of the curve approaches a constant value, $2\,R_{av}$, rapidly at first and then more slowly, reaching its maximum at an infinite distance. At 10

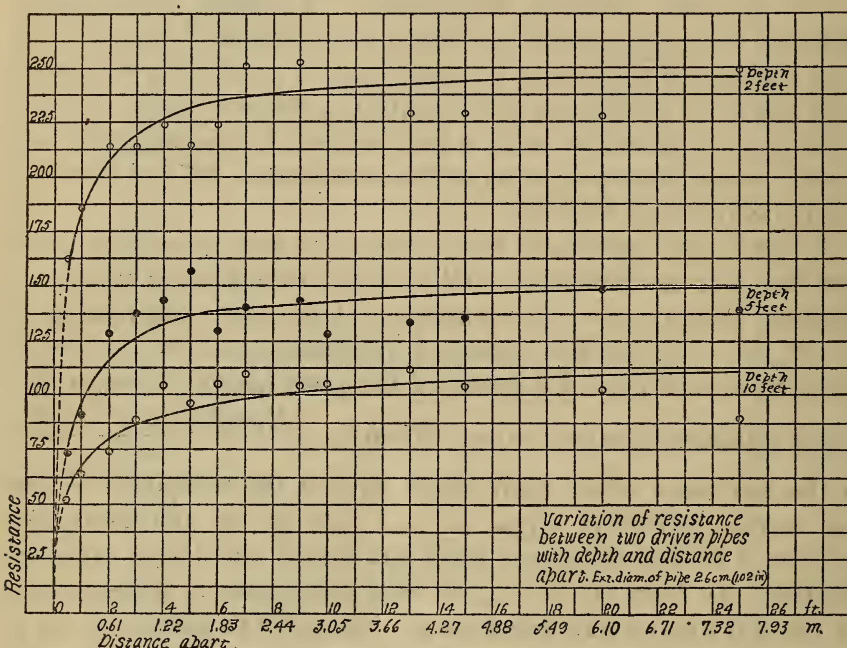

Fig. 12

feet, however, the remaining increase of resistance is in most practical cases negligible.

The foregoing method of eliminating irregularities takes no account of differences between groups, so those of 3 and 4 feet length have been omitted from Fig. 12, for the reason that the curves representing these groups would nearly coincide with some of the others. As in Table 1, the results of Table 2 have probable errors of 2 or 3 per cent because of fluctuations of line voltage while readings were being taken.

(c) Variation of Resistance of Two and More Pipes in Parallel with Distance Apart and Depth. The first measurements of this series were made on the ¾-inch galvanized-iron pipe specimens previously described. Two specimens of each

group were connected and the resistance to flow of current away from them measured by the ammeter-voltmeter method. This was done for each pair of specimens in each group. The results are given in Table 3, the irregularities having been eliminated in much the same way as under (*b*); for if two pipes are in parallel and at

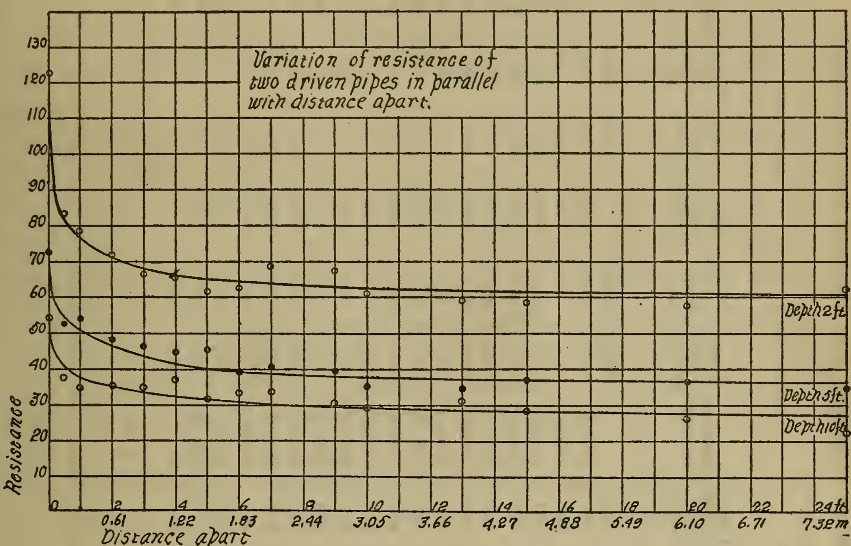

FIG. 13

a great distance from each other, the combined resistance to flow of current away from them may be expressed by $R'' = \frac{R_1 R_2}{R_1 + R_2}$, the well-known formula for the resistance of conductors in parallel, in which R_1 and R_2 are the measured resistances to flow of current away from each of the pipes. Moreover, if the soil were everywhere of resistivity ρ, $_{av}R''$ would be equal to $\frac{R_{av}}{2}$. Hence, as in the preceding section, $R = \frac{\rho_{av}}{\rho''} R'' = \frac{R_{av}(R_1 + R_2)}{2 R_1 R_2} R''$, since $\frac{R_{av}}{2}$ and $\frac{R_1 R_2}{R_1 + R_2}$ are proportional to $\rho\, av$ and ρ'', respectively. This formula is exact when the pipes are at a great distance from each other and does not introduce an appreciable error unless they are quite close together. The results for the groups of 2 feet, 5 feet, and 10 feet lengths are plotted in Fig. 13, the curves representing the corrected values of resistance and the circles and dots the observed values. At zero distance the resistance is taken to be the average of all of the specimens in the group.

TABLE 3.—Variation of Resistance of Two Pipes in Parallel With Distance Apart and Depth [a]

Resistance of each specimen.				Distance apart	Depth, 2 feet			Depth, 3 feet			Depth, 4 feet			Depth, 5 feet			Depth, 10 feet		
No.	Resistance	No.	Resistance		Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance	Specimens in parallel	Measured resistance	Calculated resistance
	Ohms		Ohms	Feet		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms		Ohms	Ohms
66	127.3	99	51.9	0.5	75–76	83.8	82.2	112–113	60.8	53.2	105–106	44.0	43.3	82–83	52.9	54.5	98–99	37.8	40.4
67	54.2	100	49.5	1	76–77	79.1	77.6	113–114	53.5	49.3	106–107	42.6	38.9	83–84	54.5	51.3	99–100	34.7	37.5
68	42.6	101	58.4	2	77–78	72.4	71.1	114–115	45.7	44.4	107–108	39.1	35.9	84–85	48.7	43.6	100–101	35.2	35.9
69	61.2	102	63.1	3	78–79	64.6	68.8	115–116	42.2	43.4	108–109	36.5	34.6	85–86	48.3	41.0	102–102	36.6	33.0
74	40.4	103	63.6	3	76–78	69.4	67.7	113–115	44.8	42.4	106–108	35.3	34.6	83–85	45.3	42.3	99–101	33.6	33.5
75	124.9	104	60.0	4	79–80	66.1	67.0	116–117	41.0	42.0	109–110	34.9	33.9	86–87	44.9	41.3	102–103	37.5	32.5
76	126.6	105	58.8	5	77–79	61.9	66.7	114–116	40.7	40.5	107–109	36.7	32.4	84–86	46.1	39.4	100–102	31.9	31.5
77	124.9	106	59.4	6	80–81	64.7	64.8	117–118	39.6	40.2	106–109	33.9	32.1	83–86	43.8	39.1	99–102	31.9	30.6
78	126.4	107	68.3	6	76–79	61.2	65.1	113–116	41.0	40.0	110–111	31.7	32.4	87–88	34.7	40.4	103–104	34.9	30.9
79	107.0	108	59.1	7	78–80	69.3	64.1	115–117	39.9	39.8	108–110	32.0	32.2	85–87	40.7	39.2	101–103	33.8	30.3
80	141.5	109	63.3	9	77–80	68.2	63.4	114–117	40.4	39.1	107–110	33.0	31.0	84–87	39.8	38.5	100–103	30.3	29.8
81	109.0	110	56.4	10	81–66	60.5	63.5	118–67	32.9	39.4	111–68	26.6	31.7	88–69	31.3	38.7	104–74	26.0	29.4
82	67.7	111	57.2	10	79–81	56.2	64.2	116–118	36.9	38.7	109–111	32.2	31.0	86–88	36.7	38.4	102–104	33.0	29.4
83	74.6	112	86.0	10	76–80	67.9	62.8	113–117	41.2	38.8	106–110	30.9	31.0	83–87	37.9	38.1	99–103	30.6	29.3
84	81.1	113	82.0	13	78–81	59.6	62.8	115–118	37.3	38.1	108–111	30.7	30.7	85–88	34.9	38.0	101–104	31.3	29.0
85	82.0	114	78.0	15	77–81	59.0	62.5	114–118	37.9	37.5	107–111	32.4	30.0	84–88	37.6	....	100–104	28.5	28.7
86	90.4	115	73.3	20	79–66	58.2	61.7	116–67	31.3	37.8	109–68	26.3	30.0	86–69	36.7	36.8	102–74	25.4	28.2
87	70.6	116	69.5	25	77–66	62.7	61.3	114–67	34.2	38.0	107–68	26.8	29.7	84–69	35.1	36.8	100–74	22.6	27.5
88	56.9	117	74.1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
98	50.4	118	70.7	....	[b] 123.4	....	....	[b] 73.5	....	....	[b] 58.1	....	....	[b] 73.1	....	....	[b] 54.7	....	....

[a] In cases where more than one pair of electrodes were available at any given distance apart, the average results were used in plotting the curves.
[b] Average resistance of specimens in each group.

The curves show that as the distance between the pipes increases the resistance decreases, rapidly at first and then more slowly, tending toward a value $\frac{R_{av}}{2}$ at infinity. After 6 feet is reached, however, the rate of decrease becomes very slow and, in fact from 6 to 10 feet becomes practically negligible. At 6 feet apart the resistance of two pipes in parallel is approximately 55 per cent of one of them and at 2 feet apart is approximately 65 per cent.

It is desirable to know whether these approximate relations between number and resistance hold when the number of pipes is increased. Accordingly, eight specimens 10 feet in length were driven in a row 10 feet apart and the resistance to flow of current away from them measured singly and in parallel. The results of these measurements are given in Table 4, also the results of measurements on four pipes 10 feet in length driven in a row 5 feet apart. In the table the second column gives the measured resistance of each specimen, the fourth the resistance to flow of current away from specimens (1) and (2); (1), (2), and (3); and so on, in parallel. The fifth column gives the resistance which each combination of specimens would have if they were so far away from each other that their respective electric fields would not interfere; that is, at an infinite distance. These values were calculated from $\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\cdots+\frac{1}{R_n}$, the familiar formula for the conductance of conductors in parallel. In Fig. 14 the results are shown in the form of a curve, the dotted-line curves representing calculated values and the full-line curves measured values. At 10 feet apart it is evident that the number of pipes could be extended almost indefinitely and the ratio of calculated to measured resistance would not be less than 80 or 90 per cent. At 5 feet apart the ratio of calculated to measured resistance is only 60 or 70 per cent, the curve indicating that this percentage decreases as the number of pipes increases. At 10 feet apart the ratio is practically constant as far as the curve goes. It is not likely that it would be practicable in many cases to drive a row of pipes of greater length than 70 feet, so the curve was not carried further. The steepness of the curve depends upon the distance apart of the pipes. For a row of given length, however, the greater the number the less the resistance.

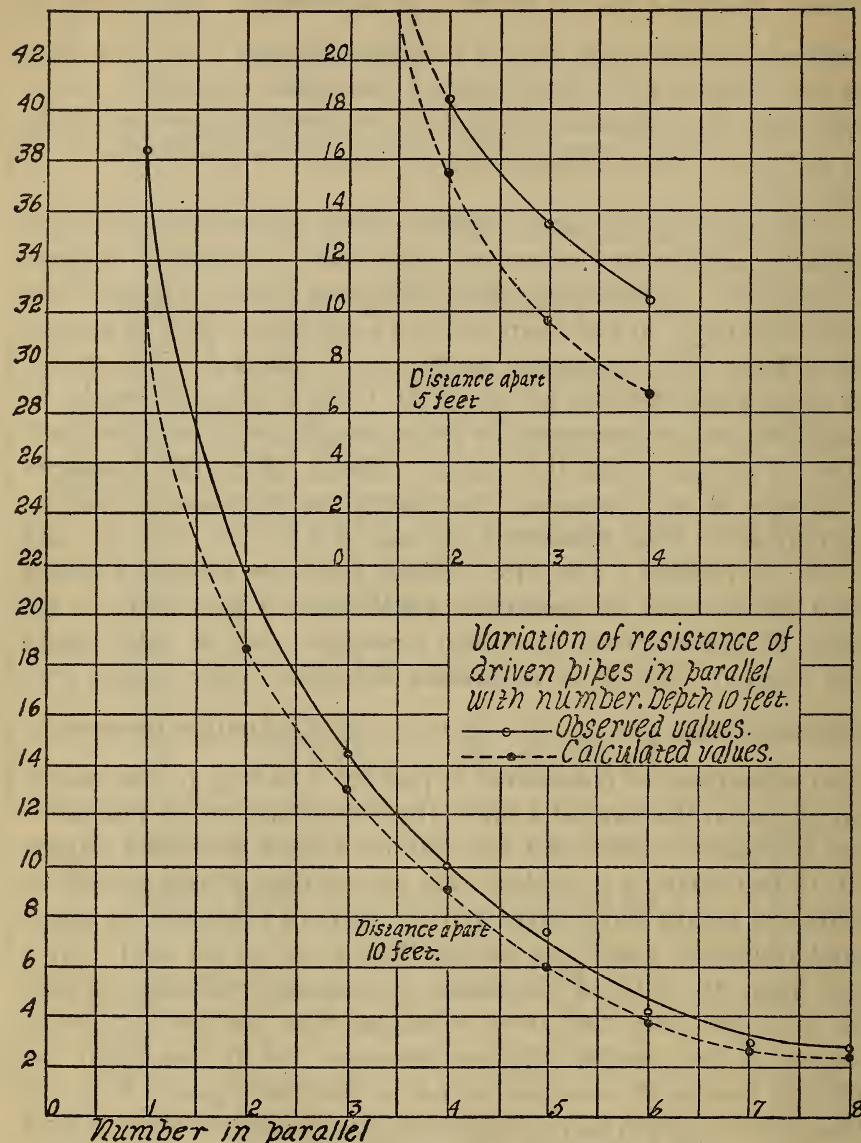
Distance apart 5 feet
Distance apart 10 feet.
Variation of resistance of driven pipes in parallel with number. Depth 10 feet.
Observed values.
Calculated values.
Number in parallel

Fig. 14

TABLE 4.—Variation of Resistance of Driven Pipes in Parallel With Number

Specimens	Resistance[a]	Specimens in parallel	Measured resistance	Calculated resistance
	Ohms		Ohms	Ohms
PIPES 10 FEET APART				
1	30.3	1,2	19.8	18.4
2	47.1	1,2,3	14.4	13.2
3	45.9	1,2,3,4	10.0	9.1
4	29.1	1,2,3,4,5	7.4	5.9
5	17.0	1,6	4.1	3.7
6	9.9	1,7	2.9	2.7
7	9.7	1,8	2.7	2.5
8	39.7			
PIPES 5 FEET APART				
9	34.5	9,10	18.2	15.0
10	26.0	9,11	13.5	9.6
11	27.6	9,12	10.8	7.2
12	28.5			

[a]Average of numbers 1 and 2=38.7.

In some instances it is necessary to make the resistance of an earth connection as small as practicable, but space is lacking in which to drive pipes at some distance from each other. This may be the case near telephone and power poles. Referring to Fig. 13, it is seen that the first foot or so of separation between a pair of pipes has the greatest influence in reducing the resistance to flow of current. Hence, much can be accomplished by driving two or more pipes even as close as 1 foot or so from each other. This is especially to be recommended as a course to follow when pipes are driven alongside of poles. Where a single pipe is driven beside a pole and close to it, the pole, which in most cases is of much greater resistivity than the soil, shuts off a large part of the current flow, unless the pipe extends some distance below the bottom of the pole. By driving another pipe on the opposite side, the resistance to flow of current can be considerably reduced. A particular instance may be cited in which three pipes 8 feet in length were driven equidistant from one another around a pole set about 4.5 feet in the ground. Measurements of resistance gave results as shown in Table 5. These results indicate that two pipes driven on opposite sides of a pole will give a resistance of approximately 65 per cent, and three pipes at 120 degrees apart approximately 53 per cent, of that of a single pipe. It is not likely, however, that a further increase in the number of pipes would produce an additional decrease in resistance sufficient to justify the expense of driving.

TABLE 5.—Resistance of Pipes Driven Around a Pole

Specimens	Resistance of each ground	Specimens in parallel	Resistance in parallel
	Ohms		Ohms
1	53.3	1–2	34.0
2	54.1	1–2–3	28.0
3	48.0	....	....

(*d*) VARIATION OF RESISTANCE WITH CONTACT AREA.—The specimens used for this experiment consisted of four 0.75-inch pipes, and three each of 1.25-inch, 2-inch, and 2.5-inch pipes, respectively, driven to a depth of 10 feet. The measurements, the results of which are given in Table 6, were made in the same manner as those previously recorded. On account of the nonuniformity of the soil, however, the results are so irregular as to give very little indication of the way in which the resistance would vary with contact area if the soil were uniform.

From this table it appears that the resistance to flow of current away from a 2.5-inch pipe is nearly as great as from a 1.25-inch pipe. This, of course, is not the case, at least not to the extent indicated by the observed values. A clearer idea of the variation of resistance with size of pipe may be obtained by making use of the observation equation $R=\frac{\rho}{2\pi C}$ as in some of the previous work, than by comparing the observed values themselves. As stated heretofore, R is the resistance to flow of current away from the electrode, ρ the resistivity of the soil, and C the electrostatic capacity in free space of the pipe and its image above the surface of the ground.

TABLE 6.—Variation of Resistance of Driven Pipes With Contact Area [a]

Specimens of each size	Size of pipe, internal diameter	External diameter of pipe	Electrostatic capacity	Average resistance	Calculated resistance
	Inches	Centimeters		Ohms	Ohms
....	....	0.5	39.1	([b])	40.2
....	....	1.0	43.6	([b])	36.1
....	....	1.5	45.5	([b])	34.5
....	....	2.0	47.7	([b])	32.9
4	0.75	2.6	49.6	38	31.7
3	1.25	4.2	53.8	26	29.2
3	2.0	6.0	57.3	27	27.4
3	2.5	7.3	59.6	24.5	26.4

[a] Depth—10 feet.   [b] No observations.

In Table 6 are given the values of C for the different sizes of pipe on which measurements were taken and also for smaller sizes to enable extending the curve back toward the axis of ordinates. In calculating C the formula for an ellipsoid of revolution, $C = \dfrac{L}{2 \log_\epsilon \dfrac{2L}{d}}$, was taken as the nearest obtainable approximation to the real value in the same way as under (*a*) where variation of resistance with depth was discussed. Substituting the measured

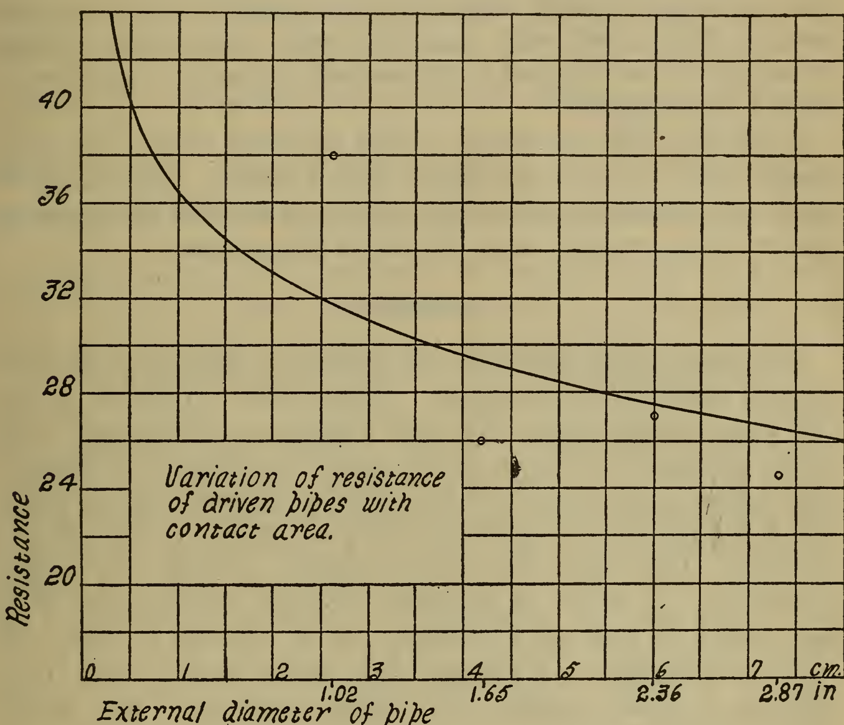

FIG. 15

values of resistance and corresponding values of C in $\rho = 2\pi CR$, the average value of ρ is found to be 9870 ohms per cm³. From this, in turn, the resistance for each size of pipe is calculated as if the resistivity of the soil were uniform. These calculated values of resistance are given in the last column of Table 6 and have been used to plot the curve of Fig. 15. The circles represent the observed values of resistance, the distance of the point above the curve being practically equal to the sum of the distances of the three points below the curve. The curve may, therefore, be taken

as a fair indication of the results which would be obtained in uniform soil, and shows that as the diameter of the pipe, and consequently the area of contact, increases the resistance decreases at a steadily decreasing rate. For instance, increasing the external diameter of the pipe from 1 to 2 cm (0.394 to 0.787 inch) decreases the resistance 9.34 per cent, from 2 to 3 cm (0.787 to 1.18 inches), 5.88 per cent, from 3 to 4 cm (1.18 to 1.57 inches), 4.84 per cent, and so on. Doubling the diameter or increasing it from 1 to 2 cm, 2 to 4 cm, and 4 to 8 cm (0.394 to 0.787 inch, 0.787 to 1.57 inches, and 1.57 to 3.15 inches) cause decreases of resistance of 9.34 per cent, 10.6 per cent, and 11.85 per cent, respectively. These values have been checked experimentally by other investigators, notably by Creighton.[22]

In driving pipes, therefore, it does not seem wise to use sizes smaller than 0.75 inch nor larger than 2 inches. Between these limits mechanical considerations determine whether the larger or smaller sizes should be used, as will be shown later.

2. PLATES

The use of buried plates for the purpose of grounding electrical systems seems to be decreasing. This is due, no doubt, to the fact that in most places the same results can be obtained with driven pipes as with plates, and at much less expense. Nevertheless, it may in some cases be necessary or advisable to use them, and it is, therefore, of interest to discuss their electrical characteristics. The discussion which follows, however, is largely theoretical. It would be desirable to obtain experimental data upon which to base the discussion, but in the case of plates the expense of obtaining consistent data seems greater than their importance would justify. To obtain consistent data would require observations on a great many specimens, since there is no practicable way of eliminating irregularities due to nonhomogeneity of the soil except by taking the average of a large number of measurements. In this investigation, therefore, the number of plates buried was limited to 12, of different sizes, which were put down mainly for the purpose of determining the variation of resistance with seasons and the effects of coke and salt.

(*a*) Variation of Resistance with Depth.—If a circular thin metal plate is embedded in the surface of the ground to a depth

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[22] General Electric Review, 15, pp. 15 and 66.

equal to one-half its thickness, the resistance to flow of current away from it can be expressed by $R=\frac{\rho}{2\pi C}$, where ρ is the resistivity of the soil and C is the electrostatic capacity in free space of the plate. In this case $C=\frac{d}{\pi}$, where d is the diameter. If, now, the plate is sunk below the surface of the ground, the value of C which must be used in the formula for R is that of the combination of the plate and its image.[23] When the plate is so far beneath the surface that its image may be considered as at an infinite distance away from it, C becomes equal to $\frac{2d}{\pi}$. In passing from the surface of the ground to a great depth, therefore, the resistance to flow of current away from the plate changes from $R=\frac{\rho}{2d}$ to $R=\frac{\rho}{4d}$. This holds for a plate of any shape—that is, the resistance at the surface of the ground is twice that at a great depth, if the resistivity of the soil is uniform—and the shape of the curve showing variation of resistance with depth would be something like that of the curves in Fig. 13, showing variation of resistance of two driven pipes in parallel with distance apart, because the rate of change of C with increasing distance would be much the same. At least, R would decrease rapidly with the first few feet increase in depth and then more slowly, approaching a constant value at an infinite depth. Hence, for plates of ordinary size—that is, of areas from 10 to 20 square feet—the depth in conducting soil should be from 5 to 8 feet, since the curves of Fig. 13 indicate that greater depths would not show a further marked decrease of resistance. In fact, for a plate or other electrode of any size or shape, when the depth is such as to make the distance between the electrode and its image several times the dimensions of the electrode, increasing the depth will not result in a further marked decrease of resistance, because at those distances the rate of increase of C with increase of distance becomes very slow.

(*b*) Variation of Resistance with Area of Plate.—Referring again to the example of the circular plate embedded in the surface of the ground, it will be seen that the resistance to flow of current away from it varies inversely as the diameter; that is, doubling

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[23] See Appendix III.

the diameter, and thus quadrupling the area of such a plate, halves the resistance. On the other hand, for a plate of rectangular shape which is very long in comparison with its width, quadrupling the area by increasing the length much more than halves the resistance. A particular instance may be given in which increasing the length of a buried strip of metal 1.5 inches wide from 40 feet to 160 feet reduced the resistance from 9.6 to 3.3 ohms. For rectangular plates of which the width is one-third to one-half the length, however, the case of the circular plate more nearly represents the conditions; i. e., quadrupling the area by a proportional increase of dimensions practically halves the resistance. This relationship between area and resistance is indicated by the fact that measurements on plates buried near other other showed resistances as follows: (1) Average resistance of two plates 2 feet by 4 feet buried 5 feet deep, 32.5 ohms; (2) resistance of one plate 2 feet by 8 feet buried 4 feet deep, 24.5 ohms; (3) resistance of one plate 4 feet by 8 feet buried 4 feet deep, 17.5 ohms. Because of the nonhomogeneity of the soil, however, these data must be taken only as indicating the relationship mentioned above and not as a check upon it.

To gain an idea of the rate at which resistance to flow of current away from a plate decreases with increasing size, the curve shown in Fig. 16 is given. This curve represents values calculated from the formula $R=\frac{\rho}{2d}=\frac{\rho}{4}\sqrt{\frac{\pi}{A}}$, where A is the area of the circular plate. The value of ρ in this case is assumed to be 7000 ohms per cubic centimeter, or very nearly the value found in one or two cases of driven pipes previously given. This curve shows that when a circular plate embedded in the surface of the ground reaches an area of 20 or 30 square feet the rate of decrease of resistance with increasing area becomes very slow. This represents, roughly, the conditions for a plate of rectangular shape beneath the surface, so it appears that the area of a single plate can not economically be increased beyond these dimensions. As indicated below, it requires much less labor and material to bury two small plates at a distance from each other and connect them by a heavy wire than to bury a single large plate which will have the same resistance to flow of current away from it into the earth as the two small plates in parallel.

(*c*) Resistance of Two Plates in Parallel.—In this case measurements were made on five plates 2 feet by 4 feet in size,

which were buried at different distances from one another in rather stony clay soil. They were laid in a row with distances between ends as indicated in Table 7, where the results of the measurements are given. Nos. 32, 33, and 36 were buried on edge in trenches 6 feet deep; Nos. 34 and 35 were buried flat in holes 5 feet deep. The center lines of those on edge were therefore at the same depth as the plane of those which were laid flat.

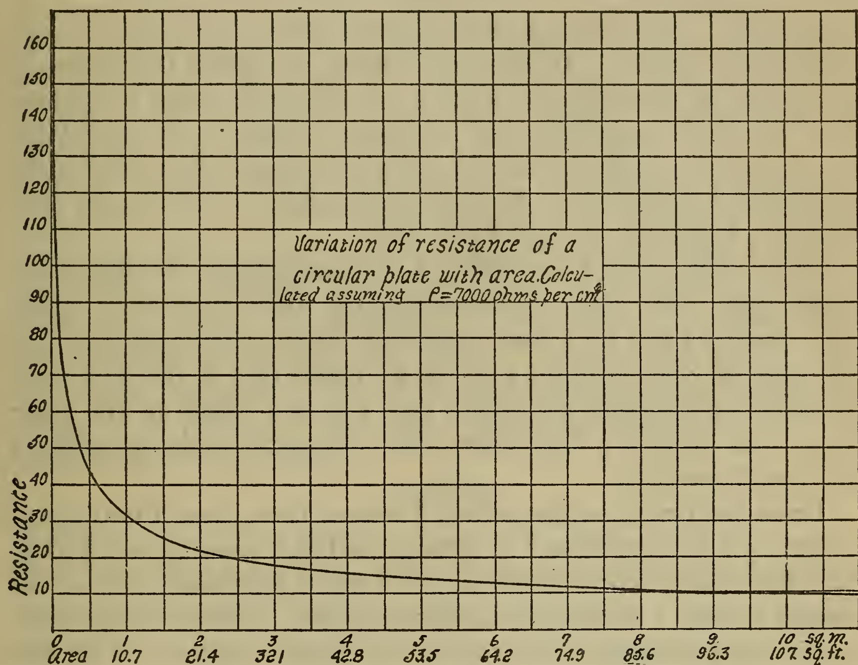

Fig. 16

The measurements of resistance were made by means of the ammeter-voltmeter method.

TABLE 7.—Resistance of Two Plates in Parallel

Plates	Resistance	Plates in parallel	Distance between ends	Measured resistance	Calculated resistance	Ratio of calculated to measured resistance
	Ohms		Feet	Ohms	Ohms	Per cent
32	31.2	32–33	1	18.8	14.5	77.2
33	27.2	33–34	5	16.1	13.6	84.4
34	27.4	32–34	10	16.2	14.5	90.0
35	44.3	32–35	29	18.7	18.3	97.8
36	31.6	35–36	30	18.6	18.4	99.0

The resistance of each specimen was first measured and then the resistances of the different pairs in parallel. From the results of the measurements on each specimen have been calculated the resistances which the different pairs in parallel would have if they were at an infinite distance apart. These values were obtained by applying the formula for the resistance of conductors in parallel, or $R=\frac{R_1 R_2}{R_1+R_2}$, R_1 and R_2 being the resistances of the individual specimens. The results of these calculations are given in the sixth column of Table 7. In the last column are given the ratios of calculated to measured resistances. From these ratios it appears that to obtain practically the minimum resistance for two plates in parallel they must be placed 25 or 30 feet apart. At 10 feet apart the ratio of calculated to measured resistance is about 90 per cent and at 1 foot apart about 77 per cent.

It has been stated heretofore that quadrupling the area of a rectangular plate, say, by increasing the dimensions from 2 feet by 4 feet to 4 feet by 8 feet, practically halves the resistance. In the case of Nos. 32 and 33 it will be noted that if the area were doubled by doubling the length and the two halves of the plate were then moved 1 foot apart, the resistance would be reduced by about one-third.

From the foregoing discussion it seems, then, that if two plates 2 feet by 4 feet are buried in uniform soil at a distance of 25 to 30 feet from each other, practically the same resistance will be obtained as with a single plate 4 feet by 8 feet. Moreover, the excavation and material required for the smaller plates will be but little more than half that for the larger plate. To bury a number of small plates would, of course, require considerable ground space, and where this is not available it would be impracticable; but where space is available, the required conductance can be more economically obtained with the small plates in parallel than with a single large one. It should be stated that the sizes of the small plates here referred to approximate 20 to 30 square feet. Up to that size it is economical to increase the area of the plate in order to decrease the resistance. When less resistance is required than these sizes will give, however, economy lies in an increased number of plates.

(*d*) Plates on Edge v. Plates Laid Flat.—In some cases it may be more advantageous to bury plates on edge than flat. In the first place, if the width of the plate is more than 2 feet less excavation may be required, because the trench need only be

wide enough to work in. It should be deep enough, however, to give an average depth equal to the depth which would be given if the plates were laid flat. In the second place, when a plate is placed on edge better contact can be made, usually, with the ground. In filling the trench the earth can be rammed on both sides of the plate, making good contact over the entire surface. On the other hand when a plate is laid flat it may rest on humps in the bottom of the trench and prevent good contact with the ground at all points. This is a condition which is very difficult to avoid. It is likely, however, that after a plate has been in place for some time, settlement will take place to a sufficient extent to eliminate the humps, unless the ground is very hard or stony. Nevertheless, to have good contact from the start is very desirable.

In the course of this investigation measurements were made on several plates, part of which were laid flat and part on edge. In the case of those laid flat there appeared to be a tendency for the resistance to be higher at the start than in the case of those on edge, with considerable decreases in the first few months, indicating settling as pointed out above. On the other hand, after settlement had taken place, there was no indication of a marked difference of resistance that could not be attributed to the nonhomogeneity of the soil.

3. STRIPS

Where bedrock is near the surface of the ground, it is in many cases out of the question to drive pipes or to dig deep enough to make an effective ground connection with plates. Moreover, the ground in such places is likely to be very dry, particularly during periods when there is little rain, for there is but slight opportunity for storage of moisture deep in the ground during wet seasons to be absorbed by the surface strata through capillary action when periods of drought occur. The best procedure under such circumstances is to connect to earth by burying narrow strips of metal in trenches dug as deep as the rock layer will allow. Because of the high resistivity of the soil which is encountered in dry seasons, it is necessary to have a ground connection of considerable extent, and metal in the form of narrow strips offers the most efficient means of obtaining it. This is shown by the fact that for a given amount of metal the strip form can be made to give a greater value of the electrostatic capacity, and hence a lower value of resistance, than any other, as mentioned under "Resistance of ground connections," Section II.

The use of buried strips is most likely to be necessary in the case of lightning-rod systems, but may be made to serve any purpose for which a ground connection may be required. For lightning rods, however, this type of ground connection is very desirable where the soil is shallow, and it may be said further that its use in soils of high resistivity will be found advantageous whether the conditions are such as to prevent the use of driven pipes or not. Its desirability in this case, especially if a considerable network of strips is used around a building, arises from the facility with

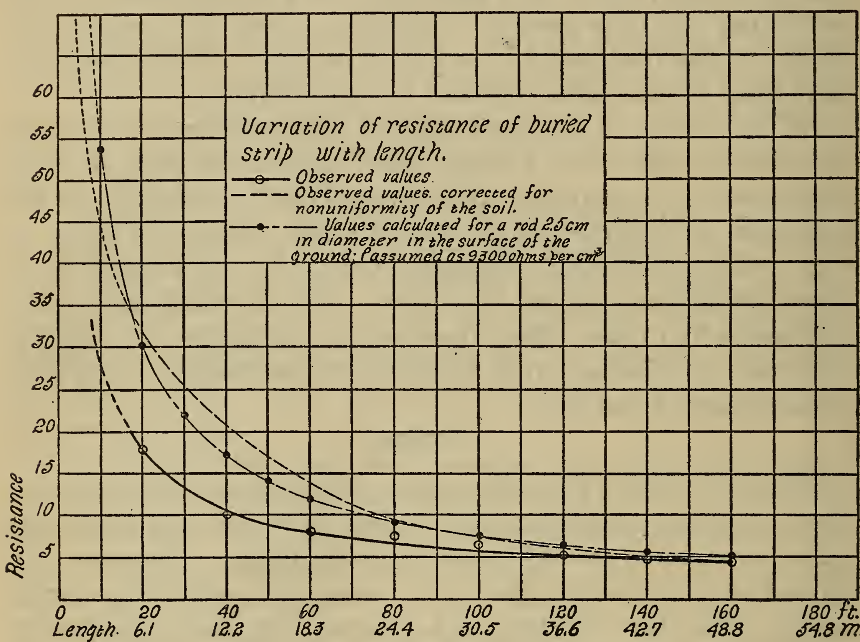

FIG. 17

which it can pick up the earth charge when a lightning stroke occurs. As pointed out heretofore, if conditions exist favorable [4] to a lightning stroke, the charge on the earth covers a considerable area, of which the building may be the center, or at least the point toward which the stroke is likely to be directed. When the stroke occurs, there is a tendency for the charge to rush toward the building, and it is obvious that a network of metal in the ground will collect this moving electricity with greater ease than ground connections at a few points, which in this case would necessarily be of high resistance.[5]

On the other hand, to make a ground connection by means of strips requires a large amount of ground space, and where this

is lacking their use is, of course, impracticable. In addition considerable excavation is required. Nevertheless, there are many places where their use is practicable and it is possible to get an effective connection to earth with them that could not otherwise be obtained.

(*a*) VARIATION OF RESISTANCE WITH LENGTH.—In order to determine the effect of length on the resistance of a ground connection made of strips of metal, 8 specimens of galvanized strap iron 1.5 inches wide and 20 feet in length were buried in a trench 12 inches deep and 160 feet long. Each specimen had leads soldered to its ends, which were brought out of the ground so the resistance of the separate specimens, or any number of them connected, could be measured. To make certain that the ends of the specimens were fully separated from each other, a wooden stake 4 inches wide was driven between them. The resistances to flow of current away from these specimens were measured each month, and a set made on July 27, 1915, when the resistances were somewhat above their minimum value for the year, are given in Table 8. This set of measurements contains values for each specimen and for combinations of the different specimens connected to give lengths from 20 to 160 feet. The results obtained on the different lengths are shown plotted in Fig. 17.

TABLE 8.—Resistance of Buried Strips

Strips	Resistance	Strips in parallel	Length	Resistance	Resistance corrected for nonhomogeneity of soil	Length of rod (Diam 2.5 cm)	C for rod	Calculate resistance, assuming $\rho=$ 9300 ohms per cm^3
						Cm		
	Ohms		Feet	Ohms		305	27.7	53.4
3	17.7	3	20	17.7	31.6	609	49.2	30.1
						914	69.3	21.4
						1220	88.6	16.7
4	13.6	3–4	40	10.1	20.5			
						1524	107.4	13.8
5	25.5	3–5	60	8.2	13.6	1829	125.7	11.8
6	48.2	3–6	80	7.5	9.0	2438	161.0	9.2
7	39.8	3–7	100	6.5	7.1	3050	195.3	7.6
8	21.2	3–8	120	5.2	5.9	3660	229.5	6.5
9	39.5	3–9	140	4.8	5.1	4270	262.5	5.6
10	47.6	3–10	160	4.4	4.4	4880	295.0	5.1
Av.	31.6							

It will be noted in Table 8 that the resistances of Nos. 3 and 4 are much lower than the average for all of the specimens, which is 31.6 ohms. The effect of these low values for the resistances of Nos. 3 and 4 is to depress the left-hand end of the curve of observed values in Fig. 17 and make the right-hand portion flatter than it should be. This arises from the nonuniformity of the soil, whereas if the soil were uniform, the resistance of No. 3 would be 31.6 ohms instead of 17.7, and that of Nos. 3 and 4 connected would be more than 10.1 ohms, the value shown by the table. To give an idea of the slope the curve would have if the soil were uniform, it is necessary to correct the observed values of resistance by means of the formula $R=\frac{R_{av}}{R_1}R'$, where R' is the observed value, R_{av} the average of all the individual specimens, in this case 31.6 ohms, and R_1 the average of the resistances of the individual specimens used in obtaining R'. This is the same as multiplying the observed values by $\frac{\rho_{av}}{\rho_1}$, where ρ_{av} is the resistivity of the soil corresponding to the measured resistance to flow of current away from all of the specimens connected and ρ_1 the resistivity corresponding to R' or the measured resistance to flow of current away from any number of them connected. The values obtained in this manner are also plotted in Fig. 17.

Furthermore, for the purpose of comparison, there is also plotted in Fig. 17, a curve obtained by calculating values of resistance for a rod 1 inch (2.5 cm) in diameter embedded in the surface of the ground to a depth equal to its radius. These values of resistance were calculated from $R=\frac{\rho}{2\pi C}$, C being obtained for the different lengths of rod from the formula $C=\frac{L}{2\log_\epsilon\frac{2L}{d}}$, where L is the length of the rod and d its diameter. The quantity ρ was arbitrarily assumed to be 9300 ohms per cubic centimeter to make the curves for calculated and corrected values nearly coincide.

It appears from these curves that if the length of a buried strip is doubled, the resistance to flow of current away from it is practically halved. In particular, in the case of the rod, when the length is doubled, the calculated resistance is decreased about 45 per cent. In the case of the buried strip, when the length is

increased from 20 to 40 feet the corrected values show that the resistance is decreased about 35 per cent; from 40 to 80 feet, 56 per cent; and from 80 to 160 feet, 51 per cent. When the length of the rod is increased from 20 to 160 feet the calculated resistance is decreased 83 per cent, while in the case of the strip the decrease is 86 per cent. The observed values do not check with these so far as decrease of resistance with increasing length is concerned, for the reason that the trench in which the specimens were buried extended from a region where the resistivity of the soil was of one value to another where it was nearly twice as great, as shown by the resistances of Nos. 3 and 10 in Table 8.

All of the values of resistance mentioned above were obtained on strips lying in a straight line. It is obvious that in this position, if the resistivity of the soil is uniform, the resistance to flow of current into the earth is less than in any other because the value of C is greatest. If the strip were curved or coiled, the resistance would be greater because C would be less. In burying strips, therefore, it is well to remember that for a given length of strip the wider the distribution the more effective the ground connection that will be obtained, unless the resistivity of the soil is nonuniform, and then it is best, in some cases, to put the metal where the resistivity is least. In most places local conditions as to resistivity of the soil will be a large factor in determining the way in which a ground connection is to be made.

(*b*) Variation of Resistance With Depth.—Where buried strips are used, it is not likely that the depth at which they are placed can be arbitrarily chosen, because, in general, the depth that can be attained will be determined by the obstruction which prevents the use of driven pipes. Nevertheless, in some instances it may be well to know something of the effect of depth. This case is similar to the one previously considered of resistance to flow of current away from two driven pipes in parallel. In fact, if a pipe of the same size as the driven pipes were substituted for the strip, the two cases would be exactly the same, for in the case of the driven pipes the electrostatic capacity C applies to the combination of the pipes and their images above the surface of the ground, while in the case of the buried pipe the value of C is the same if the depth is one-half the distance between the driven pipes and the length is the sum of that of one of the driven pipes and its image. The fact that in the case of the driven pipes the surface of the ground cuts the axes of the pipes perpendicularly

and midway between their ends, whereas in the case of the buried pipe the surface of the earth passes parallel to the axis of the pipe and midway between the pipe and its image, does not make a difference in resistance if the resistivity of the soil is the same in the two cases. It follows, therefore, that the resistance to flow of current away from a pipe 20 feet in length buried 3 feet in the ground will be the same as from two driven pipes 10 feet in length and 6 feet apart. Moreover, the curve showing decrease of resistance with increase of depth in the case of the buried pipe will be of exactly the same value and shape as the curve showing decrease of resistance with increase of distance in the case of the driven pipes. For the strip the shape of the curve would not be much different, except, perhaps, when very near the surface of the ground. At a depth of a few centimeters the curves would be practically of the same shape. In burying strips, therefore, it would not be expected that after a depth of 3 feet had been reached there would be a further marked decrease of resistance with increasing depth, because for driven pipes 10 feet in length the rate of decrease of resistance with increasing distance apart becomes very slow after 6 feet is reached. For strips of great length this depth would probably be somewhat increased, but not appreciably under lengths of 40 or 50 feet.

The foregoing deduction is borne out, to a certain degree at least, by data obtained on strips buried at different depths. These specimens were 20 feet long and 1.5 inches wide. One of them buried 6 inches deep showed a resistance of 43 ohms; eight of them 12 inches deep showed an average resistance of 31.6 ohms, as indicated in Table 8; one at 18 inches, 26 ohms; one at 2 feet, 13 ohms; and one at 3 feet, 17 ohms. It appears from these values that after a depth of 2 or 3 feet has been reached, there is no further marked decrease of resistance with increasing depth, but because of the nonhomogeneity of the soil these values must be taken only as an indication of the relationship mentioned above and not as a check upon it. The depth of 3 feet referred to above, means of course, in conducting soil. If there is a stratum of dry earth on top it may, in some instances, be necessary to place strips at a greater depth than 3 feet. To go more than 3 feet in conducting soil, however, will not result in material benefit.

4. PATENTED GROUNDING DEVICES

Many patented devices for making ground connections have been put on the market by manufacturers. Some of these devices have come to the attention of the Bureau of Standards, and in all that have been tested the feature which is supposed especially to recommend them to the prospective purchaser is that they are intended to absorb water in wet seasons and give it out in dry seasons in sufficient quantities to keep the adjacent soil moist at all times and thus prevent marked fluctuations of resistance. A grounding device with this feature incorporated would be very desirable, but practically it is not accomplished by any of the designs that have been tested up to this time. For their absorptive power some of the devices depend upon charcoal and others upon substances the compositions of which are not disclosed by their makers. One consists of a perforated sheet copper cone about 2 feet in height and 6 inches in diameter at the base, which is filled with finely divided charcoal. As regards gases the absorptive power of charcoal is enormous, a given volume of charcoal being able to absorb many times its volume of gas, but as regards water its absorptive power is only of the same magnitude as that of an equal volume of earth. The quantity of water which could be stored in such a small volume of charcoal is therefore not sufficient to be of any moment, and moreover, the charcoal would tend to dry out as fast as the surrounding earth and not lag appreciably behind it. Hence the cone might as well be unperforated and as well be empty as filled with charcoal. The same thing is true of the other devices. As shown later, however, the addition to the soil surrounding an electrode of a soluble salt which is highly conducting in solution materially decreases the resistance in comparison with what it would be with normal earth, and insofar as the substances used in these earthing devices contribute to this effect they are of benefit; but as far as absorbing water in wet seasons and giving it out in dry seasons is concerned their effects are negligible.

As stated above, a number of these devices have been tested. Table 9 contains a summary of the results obtained and also some data which enable comparisons to be made between these special devices and driven pipes and plates. In column 5 are given the resistances of the different kinds of specimens measured August 31, 1915, when they showed the minimum recorded resistance for the year, and in column 6 are given the resistances

of the same specimens measured on December 1, 1915. Where there was more than one specimen of the same kind or size the average value is given. Because of lack of rain and decrease of temperature, the values obtained in December 1 show considerable increases over those for August 31. Column 7 gives the percentage increase of resistance.

It will be noted that none of the special devices showed a resistance markedly lower than the pipes and, in fact, in all but one case the resistance was higher. None of them showed lower resistance than the plates. The figures showing percentage increase of resistance are the most important because the special virtue of these devices is supposed to lie in the comparatively uniform resistance which they maintain. It is shown that the resistance of all the devices increased much more than that of the pipes, and in most cases more than that of the plates. It does not appear, therefore, that the use of these devices will give a result that can not be obtained with pipes, and, moreover, with pipes the cost is less.

TABLE 9.—Comparison of Patented Devices With Pipes and Plates

Specimens	Description	Length or size	Depth	Average resistance, Aug. 31, 1915	Average resistance, Dec. 1, 1915	Percentage increase
			Feet	Ohms	Ohms	
25–26	Paragon ground cones in coke	2 feet	5	39.5	62.2	54.9
27–28	do	1 foot	5	46.4	72.1	55.4
29–30–31	Maxum ground boxes in clay		5	33.2	57.4	72.9
43	L. S. Brach hydroground in clay	Large	5	39.8	61.2	53.8
44–45–46	do	Standard	5	42.2	57.1	35.3
47	do	Medium	5	37.5	52.7	40.5
48–49	Lord Manufacturing Co. disk type hydroground in clay		5	76.1	124.0	63.0
54–55	Federal Sign System cartridge ground plate in clay.	22 inch	5	42.6	71.9	68.8
56–57	do	10 inch	5	47.3	80.6	70.4
32–33 and 36	Plates on edge in clay	2 by 4 feet	6	20.3	29.9	47.3
34–35	Plates flat in clay	do	5	25.4	35.6	40.2
74 and 98 to 104	Three-fourths inch galvanized-iron pipes.	10 feet	10	35.6	47.1	32.3

5. WATER PIPES

As a means of grounding electrical systems water pipes easily come first in point of desirability. In the first place, on account of their great extent they offer but little resistance to flow of current away from them into the earth, the total resistance of

water-pipe ground connections being found in most cases to be but a fraction of an ohm. A resistance of 2 ohms would be extraordinarily high. In the second place, they are easily accessible at service pipes or at other places; and in the third place, ground connections to them are economical in first cost, are easy to inspect, and are permanent. Moreover, the areas covered by electric lighting systems are approximately the same as those covered by water systems, within city limits at least, so it is practicable to ground to them in nearly all cases where ground connections are required. To use the water pipes is, therefore, highly advantageous in many cases, and is especially so where low-voltage alternating-current circuits must be grounded through a low resistance for the sake of personal safety. In this connection it should be emphasized that because of the high degree of security obtained from electrical dangers, the chief advantage is to the public, and in view of this fact, no obstacle should be placed in the way of grounding to water pipes. At the same time, however, it must be shown that the use of water pipes for making ground connections is not in any appreciable degree a disadvantage to the pipe-owning utility. In the past it has been stated that trouble for the utility would arise from three sources, viz, (1) electrolysis by stray currents from grounded circuits; (2) danger to employees while working on service or other pipes to which circuits were grounded; (3) complications from allowing a second public-service utility the use of the pipes. The factors which affect the resistance and effectiveness of water-pipe ground connections and the extent of the possibilities that the use of water pipes for grounding may inconvenience the water utility are discussed under the following heads: (*a*) Resistance of water-pipe ground connections; (*b*) electrolysis by alternating current; (*c*) electrolysis by direct current; (*d*) heating of pipes by current flow; and (*e*) extent of danger to employees of the water utility.

(*a*) Resistance of Water-Pipe Ground Connections.—As stated above, the resistances of water-pipe ground connections are found in most cases to be a fraction of an ohm. Where these low resistances exist, however, it will be found that the pipe joints for a considerable distance from the point of connection give as good metallic contact as will be the case with lead or screw joints, which under favorable circumstances have resistances of only a few thousandths of an ohm. On the other hand, where high resistances exist they will almost always be accompanied by

high-resistance joints such as those made with cement or "leadite," which may have resistances of several ohms or even several hundred ohms. The extent to which the effect of the resistance of the pipe may exceed the effect of the resistance of the soil in hindering flow of current through a water-pipe ground connection is indicated by reference to the case of the buried strip previously considered. It was there shown that if the length of a rod or strip buried in the ground is doubled, the resistance is practically halved. The measured resistance to flow of current away from a buried strip 160 feet in length was found to be about 5 ohms. Assuming the law of variation of resistance with length, as stated above, to hold and neglecting the resistivity of the metal, it is readily seen that if the length were increased from 160 feet to 20 miles the resistance to flow of current away from the strip would be decreased from 5 ohms to a value of the order of 0.007 ohm. Furthermore, if a water pipe 6 or 12 inches in diameter were substituted for the strip, the resistance would be less than 0.007 ohm. Hence, it appears that for water systems of considerable extent, the portion of the total resistance contributed by the surrounding earth is very small. On the other hand, measurements in many cases have shown that an average value for the total resistance is about 0.25 ohm, indicating that the resistance of the pipe contributes an important part and must be considered. In fact, cases may arise where many joints of high resistance in a pipe may make it undesirable as a means of grounding electrical circuits. An example of such a pipe would be one laid with cement joints, or with other insulating joints at short intervals, such as those mentioned above.

In grounding to pipes, however, a distinction must be made between cases where a low resistance to flow of current from an electrical circuit into the earth is desired and those where the object is to keep an electrical circuit, or a conducting body near an electrical circuit, at the same potential as a near by section of pipe. For, even though a length of pipe may have so many joints of high resistance as to make it useless as a ground connection designed to carry considerable current, it may still have sufficient conductance to carry currents large enough to produce severe shocks at moderate voltages in the event of persons making contact with circuit and pipe simultaneously. To prevent accidents of this kind it may be advisable to ground to pipes in some instances even though the resistance to the earth itself is very high.

Cases where such grounding would be necessary are most likely to arise in buildings.

A point which should be mentioned here is the effect which changes in the resistivity of the soil have on the total resistance of a water-pipe ground connection. In the types of ground connections previously considered, the resistivity of the soil is one of the most important factors. To double the resistivity of the soil where one of these ground connections is made would double the resistance. With water pipes, however, the part of the total resistance contributed by the soil is small, unless the resistivity is extremely high, so considerable changes due to drying or other causes will not seriously change the total resistance. In fact, for water-pipe systems of great extent, the resistivity of the soil might change from a value of say 5000 ohms per cubic centimeter to many times that value without markedly affecting the total resistance. In making ground connections of this type, therefore, little attention need be given to the kind of soil in which the pipe is laid. On the contrary, the most important matter in this case is that of high conductance of the pipe joints, such as would be found with lead or screw joints.

It is of interest to compare the average resistance of water-pipe ground connections with that of other forms. For instance, it has been shown previously in this paper that if pipes 10 feet in length are driven in a row 8 or 10 feet apart, their resistance in parallel is about 15 per cent more than it would be if they were at an infinite distance apart, or is not far from inversely as the number. Assuming a single driven pipe in a certain locality to have a resistance of 15 ohms, which is a rather low value, to obtain a resistance of 0.25 ohm would require 50 or 60 pipes 10 feet in length driven in a row 10 feet apart and electrically connected. To obtain the same resistance with plates would require about the same number, unless they were very large, and in addition, it would be necessary to place them more than 10 feet apart. This is plainly impracticable.

At the same time it must be granted, of course, that it is practicable by the use of driven pipes or buried plates to obtain a ground connection which is amply effective for some purposes. For example, a ground connection can be made which will serve satisfactorily for low-voltage alternating-current circuits where transformers are small and fed by lines of limited current-carrying capacity, and an appreciable degree of protection may be obtained

in this way for lines of almost any capacity. As the power rating of the lines and transformers increases, the resistance presented by the ground connection must decrease if ample protection is to be afforded. The practicable limit of decrease of resistance with driven pipes or buried plates is soon reached, and for circuits of large capacity it is imperative that some other means be found. The most obvious solution of the problem is to connect to water pipes which, in most cities as mentioned heretofore, cover approximately the same areas as the electrical systems. Other means should be resorted to only when the water pipes are out of reach.[24] In the case of lightning rods on the other hand, and also of lightning arresters, machine frames, and any other cases where low resistance is not so essential, driven pipes or plates may serve very well, but there is no case in which water pipes having low-resistance joints can not be used to advantage.

(*b*) Electrolysis by Alternating Current.—Such electrolytic damage from alternating currents as may accrue because of earthing electrical circuits to water pipes will, as a rule, be due to currents set up in the pipes by the circuits themselves. It is possible, of course, that there may, in some cases, be stray currents on the pipes from alternating current railways, and grounding electrical circuits to the pipes at several points may divert part of the flow of these currents, as indicated in the next section in regard to direct currents. But these cases are few, and as shown below the extent of the electrolytic damage negligible, so the consideration here given is confined to stray currents set up in the pipes by the grounded circuits, either under normal operating conditions or under conditions of faulty insulation. Referring to Fig. 18, *A* represents an extensive low-voltage alternating-current circuit which is grounded at a number of points to service pipes, these service pipes being all connected to the same water main. It is readily apparent that under normal conditions of operation, or with insulation everywhere in good condition, some current would flow in the pipes, for with an even slightly unbalanced load on the system, current would flow in the middle wire, and because of the accompanying differences of potential between the points *e*, *f*, and *g*, the pipes would carry part of the current, the total current being shared in inverse proportion to the resistances. The current in the middle wire, however, is usually only a small part of the full-load current, and for that reason the current flow in the pipes is not likely to reach serious proportions.

[24] See rule 94, Appendix II.

On the other hand, normally there can be no interchange of current between circuits *A* and *B*. In order for this to occur, the flow would have to take place from *A* through earth wires *a*, *b*, and *c* in parallel, over the water pipe to wire *a* and circuit *b*, and back to *A* on the high-voltage line. Two layers of transformer insulation prevent this, so such an interchange of currents is practically impossible, unless faults develop in the insulation of both transformers. If this should be the case, fuses 1, 2, 3, or 4 would be likely to blow and isolate the low-voltage circuit, or, if they did not blow, the current would be limited to their rated capacity.

With a low-voltage circuit connected to the pipes at a single point as in *B*, Fig. 18, there is obviously no opportunity for any

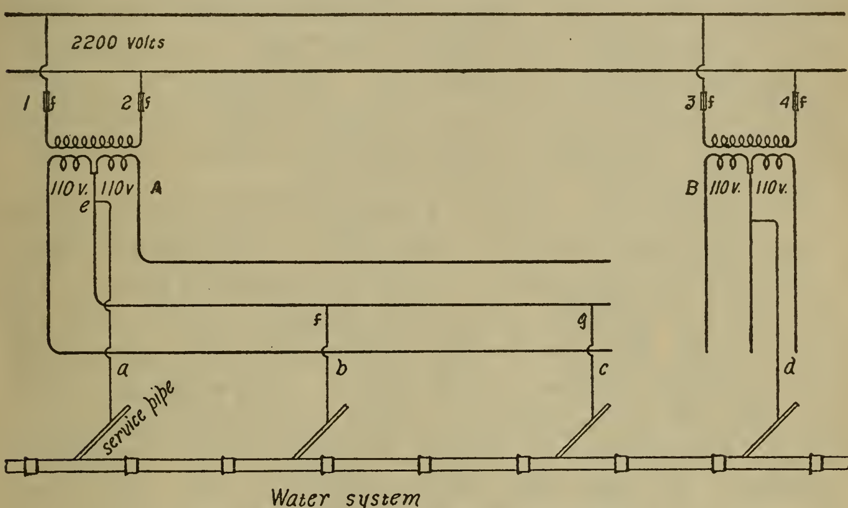

FIG. 18.—*Parallel ground connections to water system*

but the very slightest flow of current into the pipes over wire *d* as long as the insulation remains intact. The slight current that would flow would be due to electrostatic capacity and leakage effects and would hardly be measurable by any ordinary means.

With a condition existing such as that shown in Fig. 4, however—i. e., a contact between wires—considerable current might flow. If the leak should occur to circuit *A*, Fig. 18, for example, the current would pass from one side of the high-voltage line through the fault to circuit *A* and to the pipes over ground wires *a*, *b*, and *c*, whence it would flow through the earth back to whatever accidental grounds there happened to be on the opposite side. This current flow would obviously continue until the circuit was opened either by automatic cut-outs or by switches.

30263°—18——7

Nevertheless, granting that under normal conditions of operation slight alternating currents may flow continually and that in the event of failure of insulation large currents may flow temporarily, it has repeatedly been shown by experiments both by the Bureau of Standards and by others that the damage which may result by electrolysis from such currents is practically negligible.[25] These experiments, made on both iron and lead, show that with alternating current at commercial frequencies the amount of metal dissolved is but a fraction of 1 per cent of that dissolved by direct current, the quantities of electricity passed being the same. To express the same thing in different words, it may be said that with currents in pipes which are equal in point of quantity of electricity passed, it will take the alternating current hundreds of years to accomplish the damage that would be accomplished by the direct current in a single year. Therefore, from the stray alternating currents which may be found in pipes from grounding low-voltage alternating-current circuits to them no perceptible damage through electrolysis need be feared.

(*c*) Electrolysis by Direct Current.—Electrolysis by direct current may arise where the middle wire of a low-voltage direct-current system is grounded to a pipe at a number of points. The pipe forms a conductor in parallel with the middle wire, and when current flows in the wire current may also flow in the pipe. If the resistance of the pipe is comparable in magnitude with that of the middle wire these currents will also be comparable, being shared in inverse proportion to the resistances. Practically the same effect will be produced where a direct-current system is grounded to a water system at the central station and at other places to driven pipes or plates. The combined resistance of all these pipe and plate grounds in parallel may be low enough to result in a very considerable current flow in pipes near the station. This current flow may, in some cases, be sufficient to result in time in serious electrolytic damage. Damage may also arise from direct currents where an electrical circuit of any kind is grounded to two metallically separate pipe systems, for if there are stray currents from street railways on the pipes, there may be a considerable difference of potential between the two systems, with the result that current flow may be diverted by the grounded circuit and carried into buildings or other places. Another case in which damage may arise from

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[25] Technologic Paper No. 72 of the Bureau of Standards.

stray currents from street railways is where an electrical circuit is grounded on each side of an insulating joint installed in a pipe for the purpose of mitigating electrolysis. The grounded circuit here acts as a shunt to the joint and may carry a heavy current if there is a considerable potential difference between the two sections of pipe, thus nullifying in a measure the effect of the joint.

Where direct-current systems alone are concerned, electrolysis from currents originating in the systems themselves, or in street-railway systems and being diverted by grounded circuits from their normal paths, may be obviated by making ground connections only at stations and insulating the rest of the system. No especial advantage is gained by making multiple grounds on direct-current circuits, and by using a single ground any possibility of appreciable damage by electrolysis is prevented. It should be mentioned, however, that while grounds on direct-current systems other than those at the stations are objectionable, an exception may be made in the case of connections to service boxes. These connections are desirable to prevent burning out of lamps and appliances in the event of breakage of the middle wire, and since the resistance to ground of these boxes is generally high, connections to them will not result in appreciable flow of current to earth. In the case of alternating-current systems, however, the use of multiple grounds is, as mentioned later, a decided advantage, and with slight precautions such grounds may be used in nearly all places where their use is required or desirable. The main precaution to be observed is to ground only at points between which there are no appreciable potential differences.

(*d*) Heating of Pipes by Flow of Current.—As shown heretofore, in the event of a failure of insulation in a transformer, or an accidental contact between wires, there may be considerable current flow through the ground connection, and where water-pipe grounds are used, this current may have to traverse a greater or less length of service pipe before it passes into the earth. This, of course, causes a certain amount of heat to be liberated in the pipe, and it has been stated by some that it may be sufficient to raise the temperature of the water high enough to injure the hard rubber parts of water meters. Cases of injury to the hard rubber parts of water meters have been reported, but upon investigation most of them have been found to be due to backing up of hot water from water boilers into service pipes on account of overheating.

Only one case has come to the notice of the Bureau in which there was sufficient current flow in a service pipe to heat the water to a dangerous temperature. In this a street-railway track was bonded to a service pipe which was required to carry a large part of the return current from the cars. A case of this kind, however, is exceptional, and no case has come to the notice of the Bureau in which sufficient current flow to cause heating has occurred from secondary circuits. Moreover, the likelihood of such heating occurring is small, because where there is a possibility of large currents flowing, it will, in most instances, be found that grounding is done either to a large service pipe or to several service pipes in

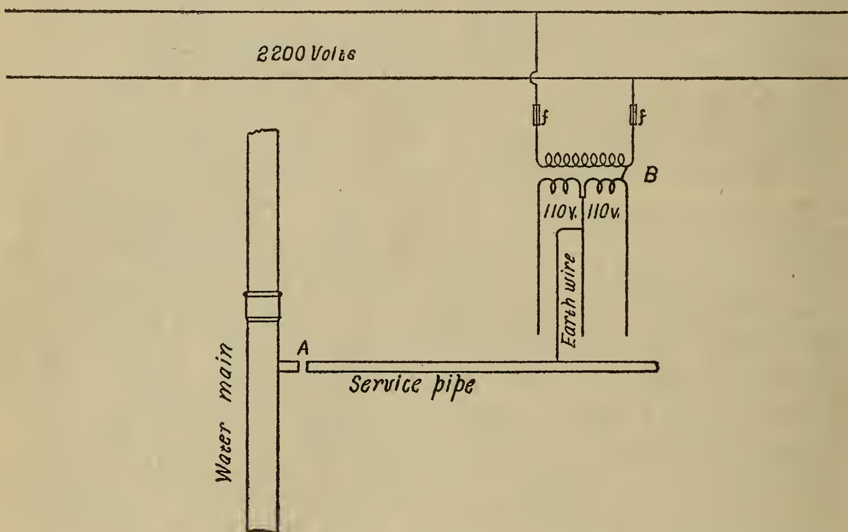

FIG. 19.—*Effect of disconnected service pipe*

parallel, in which case each service pipe carries only a part of the total current.

(*e*) EXTENT OF DANGER TO EMPLOYEES OF THE WATER UTILITY.—In general it may be stated that danger to employees of the water utility is likely to arise only under the conditions illustrated in Fig. 19. This shows a low-voltage circuit grounded at one point to a service pipe, a failure of transformer insulation having occurred at *B*. If the service pipe is disconnected at *A*, the person making the disconnection is liable to an electric shock. The severity of the shock depends upon a number of factors which have previously been discussed, and it has been shown that conditions may easily arise under which the severity would be great enough to cause death. Therefore, with low-voltage circuits

grounded at a single point to service pipes, precautions are advisable to prevent such accidents to employees of the water utility when working on them. This can readily be provided for by requiring the electric company to disconnect ground wires from service pipes when work is to be done on them and reconnect when the work is finished. This is a reasonable and sufficient requirement and has been in force in several places for years with satisfaction to both parties.

In this connection, however, it should be mentioned that the probability of employees of the water utility being injured in the manner described above is exceedingly remote. The foregoing paragraph is intended to indicate only what might occur, for, where water-pipe grounds are used, it will be found that but few low-voltage circuits are grounded at a single point; and where this occurs, the low percentage of failures of insulation, and the infrequency with which service pipes are disturbed, makes the chance of work on a service pipe and a failure of insulation occurring at the same time, almost negligible. Nevertheless, where low-voltage circuits are grounded to service pipes at a single point, the precaution of disconnecting the ground wire before beginning work on the pipe should not be neglected. On the other hand, with multiple ground connections to water pipes, as shown in Fig. 18, precautions of this kind are not necessary. Unless all of the service pipes to which ground wires have been attached are disconnected there is no danger. A person may work on one of the service pipes in perfect safety as far as electric shock is concerned if the connection to the others are undisturbed.

6. MULTIPLE GROUND CONNECTIONS

As previously indicated, it is, in many cases, desirable to ground electrical circuits at more than one point. Moreover, the general practice at the present time is to use multiple grounds, especially where connections are made to water pipes. Where driven pipes, plates, and other small electrodes are used this practice is not so general, but systems in which the custom is followed of making but a single connection to ground on each circuit are not frequently found, unless it be in the case of direct-current systems. The advantages and disadvantages of using multiple ground connections in direct-current and alternating-current systems, the precautions to be observed in their use, and the desirability in some cases of using a common ground wire are set forth below.

(*a*) Direct-Current Systems.—From considerations given in the foregoing discussion on electrolysis by direct current, it is evident that the use of multiple ground connections on direct-current systems is to be avoided to as great an extent as possible, principally on account of electrolysis effects which may arise from the diversion into metallic structures of currents from the circuits themselves. And because the currents carried by many direct-current systems are heavy, these effects may be marked, not only where water pipes are used exclusively, but also where driven pipes and plates are used, particularly if the ground connection at the power house is made to a water system and the rest to pipes and plates. A further reason why multiple grounds on direct-current systems should be avoided, especially multiple grounds to water pipes, is that return currents from electric railways may be diverted from their normal paths of flow by the grounded circuit. In direct-current systems the opportunities for this are greater than in any other because direct-current systems are used mostly in the business districts of cities where traffic is more or less congested and the density of the return current from street cars correspondingly high.

On the other hand, the advantages in the use of multiple grounds on direct-current systems are not great. In fact, in most systems very little is to be gained by making more than a single ground of low resistance at the power house or substation. In the first place, these systems being mostly underground and seldom so situated as to be liable to contact with high-voltage lines, the chance of an abnormal rise of potential against earth, even though the circuit were insulated throughout, is so small as to be of no moment whatever. Consequently, breakage of the ground wire and complete insulation from ground of the entire system, which multiple grounds are designed particularly to overcome, is not likely to prove as serious as in the case of circuits in which dangerously high voltages to ground may appear. In the second place, on account of the large size of the conductors, especially in main lines, and also because of the fact that where they are undergound they are unlikely to be subject to mechanical injury, there is very little chance of a break occurring in the middle wire. Hence, there is no need for multiple grounds to prevent the isolation of a section of line having an unbalanced load with no ground connection. As mentioned heretofore, however, connections to service boxes for this purpose need not

be abandoned, because the resistance of these boxes to ground will, in general, be high. In the third place, to have a single ground connection of low resistance facilitates the detection of accidental grounds. In direct-current systems, therefore, a single ground connection at the central station or substation not only eliminates the possibility of damage by electrolysis but serves every purpose for which grounds on direct-current systems are needed; that is, if the circuits are not exposed to contact with high-voltage lines. Where the latter is the case multiple grounds are preferable. In low-voltage alternating-current circuits, for instance, the desirability of multiple grounds for the purpose of reducing the life hazard is great enough far to outweigh any considerations which may arise in regard to electrolysis.

(*b*) ALTERNATING-CURRENT SYSTEMS.—In grounding low-voltage alternating-current circuits the use of multiple ground connections presents the following advantages: In the first place, if a circuit is connected to earth at more than one point, the protection against high voltage is not so likely to be destroyed by breakage of the ground wires as where there is but a single ground connection. In the second place, where multiple grounds are made to water pipes a high degree of safety is afforded employees of the water utility when working on the pipes. In the third place, the greater the number of connections to earth, the less the possibility of a dangerous rise of potential between circuit and ground in the event of a failure of insulation or an accidental contact between wires. This is particularly the case where driven pipes, plates, or grounds other than water pipes are used, since the total combined resistsnce of such grounds in parallel varies approximately inversely as the number. Moreover, in the event of heavy current flow to earth, overheating of the ground wires is not likely to occur because the total current is divided among a number of them. Finally, as shown already, damage from currents in water pipes set up by the circuits themselves is extremely unlikely to occur, and as will be shown, damage by diversion of stray currents from their normal paths of flow is easily avoided. Multiple grounding of low-voltage alternating-current circuits, whether to water pipes or other forms of grounds, is therefore strongly to be recommended.[26]

As just mentioned, however, cases sometimes arise in which it is necessary to guard against trouble from stray currents from street

[26] See rule 92*b*, Appendix II.

railways. Such cases are rare, of course, but they present a possibility which must be taken into consideration. For instance, if a low-voltage circuit is grounded at different points to two metallically separate pipe systems which are at a difference of potential with respect to each other due to stray currents, current will flow from one pipe system to the other over the grounded circuit. The magnitude of this current flow may be sufficient to overheat the wires, or it may be carried by the circuit into the frames of buildings, conduit, or cable sheaths and cause damage by electrolysis. A similar effect may be produced if a circuit is grounded at one point to a water pipe or street car rail which is at a potential difference of several volts from ground and at another to the steelwork of a building or some other metallic structure. The metallic structure takes the potential against ground of the pipe or rail, and danger of electrolysis ensues.[27]

Another way in which stray currents may be diverted from their normal paths of flow is by grounding a low-voltage circuit on each side of an insulating joint which has been installed in a water pipe for the purpose of mitigating electrolysis. The circuit then acts as a shunt to the joint, and the resulting current-flow over the wires may not only cause overheating or electrolysis but also in a measure nullify the effect of the joint. To avoid trouble, both on account of electrolysis and interference with the operation of the circuit, this general rule should be followed. In every case where a low voltage circuit is to be grounded at more than one point, the ground connection should be made at places between which no appreciable differences of potential exist.[28]

A statement should also be made here in regard to grounding the armor or sheathing of extended power or telephone cables to water pipes, for the same precautions must be observed in the case of these sheaths as in the case of low-voltage circuits. In fact, where it is desirable to ground any conducting body of considerable length to water pipes at more than one point, careful consideration should be given to the possibility of picking up enough stray current to cause trouble, either from electrolysis or from overheating. On the other hand, where multiple grounding is done solely by means of driven pipes or plates, the possibility of picking up enough stray current to cause trouble is practically negligible; for in the first place, the potential differences usually found between points in the soil itself do not exceed a very few volts, unless it be between points remote from each other but very

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[27] See rule 94*d*, Appendix II.

[28] See rule 94*a*, Appendix II.

near to pipes or rails carrying heavy current flow; and in the second place, the resistances of pipe and plate grounds are so high that at the low voltages encountered but very little current flow over the grounded conductor results. Hence, in making multiple grounds with driven pipes or other electrodes of small extent, little care need be exercised in regard to stray currents, but in the case of water-pipe grounds, as mentioned above, care, in some cases at least, is necessary.

Wherever such care seems to be called for, the resistance of the pipe line between the two farthest removed points of connection can be measured to make certain that no insulating joints are present. If there are no insulating joints, the resistance will, in general, be found to be but a fraction of an ohm. If there are insulating joints, it may be as much as an ohm or even several ohms. In the case of separate pipe systems, voltage measurements between them will generally give the desired information. A better method, perhaps, of finding whether a circuit can be grounded at more than one point is to ground its extreme ends with a recording ammeter in circuit and ascertain whether current flow results. If there is none, or if it does not amount to more than a very few amperes at any time during the day, grounding at more than one point may be considered practicable. If, however, the current flow is sufficient to cause unbalancing of the voltage or overheating of the wires, it will, of course, be necessary to confine the number of ground connections to one or else to several very near each other.

(*c*) Common Ground Wire.—In sections where water pipes are not available and the soil is not particularly favorable toward making grounds with driven pipes or other devices, the problem of securing adequate protection against high voltages is best solved by making use of a common ground wire. The usual form of common ground wire is illustrated in Fig. 20. Here a wire of the same size as the line wires connects a number of low-voltage circuits, with ground connections installed at each transformer and at advantageous points along the line. Thus the protection of each circuit is derived, not only from the grounds on the circuit itself but also from those on the ground wire and all of the other circuits in parallel. If the extent of the ground wire is considerable and it is grounded at many points, the degree of protection afforded, while not equal to that offered by water pipes, may be rated as next to it.

In providing grounds for such an installation as that described above, advantage should be taken of local conditions—that is, rather elaborate ground connections should be made in locations which are the most favorable as regards soil and moisture—and use should also be made of local water systems, driven wells, and other underground metal. If care in this respect is exercised, good results may be obtained even where the soil consists principally of gravel, sand, or stones.

The cost of a common ground wire where a special wire has to be run to bridge gaps between low-voltage circuits is, of course, the same as for a line wire. Aside from this the expense necessarily incurred in excess of that which would otherwise be required is inconsiderable. It is advisable, however, to make as many ground connections as practicable, because the greater the

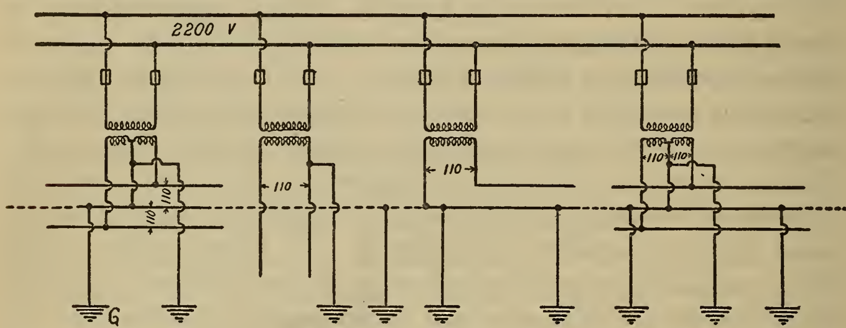

Fig. 20.—*Common ground wire system.*

number the better the protection that is afforded. This is also true whether a common ground wire is used or not. In fact, a single ground connection on a low-voltage secondary circuit should be avoided wherever possible, and multiple grounds used instead whether connection is made to water pipes or to grounds of other forms. The increase in the degree of protection is well worth the expense.

7. VARIATION OF RESISTANCE OF GROUND CONNECTIONS WITH SEASONS

The seasonal variation of resistance of ground connections is great enough in some localities to be of considerable importance. The principal factors which cause this variation are the temperature and moisture content of the soil. For changes in the temperature and moisture content of soil cause its resistivity to change between wide limits, and since the resistance to flow of current away from an electrode buried in the earth depends directly upon

the resistivity of the soil, changes in the latter will also cause changes in the resistance to flow of current. The degree to which such changes will affect the total resistance of an earth connection depends upon the extent of the electrode. With electrodes of limited extent, such as driven pipes, the part of the total resistance contributed by the metal is negligible in comparison with that contributed by the soil. Hence, changes caused by temperature and moisture content cause practically proportional changes in the total resistance. With electrodes of great extent, however, such as water pipes, the case is different. The total resistance of an earth connection made in this way may depend in larger part upon the resistance of the pipe per unit length than upon the resistivity of the soil, so changes in the latter are not likely to produce serious changes in the total resistance. The effects of the temperature and moisture content of soils on their resistivity are discussed briefly below, and some experimental data are also given which show the magnitude of the variation in resistance of ground connections with seasons that may be expected under climatic and soil conditions similar to those prevailing in the vicinity of Washington.

(*a*) Temperature Effects.—The effect of temperature upon the resistivity of soils has been studied at the Bureau of Standards,[29] and it has been found that at a temperature of 18° C the rate change of resistivity with change of temperature is about 5 per cent per degree. This value holds approximately until 0° is reached. At this point a sudden change in the rate occurs and it becomes more rapid. From -4 to $-8°$ it is about 30 per cent, from -8 to $-12°$ about 13 per cent, and from -16 to $-20°$ about 9 per cent. Reducing the temperature from $+20$ to $-19°$ increases the resistivity more than 200 times, with a sharp change in the rate of increase at 0°, of course, where the water contained in the soil begins to freeze. With decreasing temperature below 0° the resistivity tends toward values commonly associated with dielectrics. These data were obtained on a sample of clay containing 18.6 per cent of moisture and having a resistivity of 6260 ohms per cubic centimeter at 20°. With different soils, deviations from these figures may be expected but the order of magnitude will remain the same.

It is apparent, therefore, that a ground connection which is intended to be operative at all times of the year must be well

[29] Technologic Paper No. 25, Bureau of Standards, Electrolytic Corrosion of Iron in Soils.

below the frost line. In some localities in the United States where the winter seasons are severe, this may be at a depth of 6 or 8 feet; in others, it may not exceed a few inches, and there are places where the ground does not freeze at all. If at any place freezing temperatures prevail for some time, however, considerable increases in the resistance of ground connections may be anticipated, unless it be in the case of water pipes. These, in general, are laid well below the frost line, and as pointed out above, great changes in the resistivity of the soil are required to produce material changes in the resistance of ground connections made to them. Above freezing, the effect of change in temperature upon the resistivity of soil is not great, and for that reason, the resistance of water-pipe ground connections will be found fairly uniform the year round, at least as far as the effect of temperature is concerned.

(*b*) Moisture Effects.—The moisture content of soil is much more important than temperature in its effects on the resistivity at temperatures above freezing. For a particular sample of red clay, it has been found [30] that decreasing the moisture content from 22 per cent to 16 per cent increases the resistivity about 2 times, from 16 per cent to 11 per cent about 20 times, and from 11 per cent to 5 per cent about 10 times. Decreasing the moisture content from 30 per cent to 5 per cent increases the resistivity about 400 times. A decrease from 22 per cent to 5 per cent causes a change in the resistivity from 6800 ohms per cubic centimeter to 2 340 000 ohms per cubic centimeter. When air dried this soil contains about 5 per cent moisture. For different soils the resistivity for a given moisture content may differ widely, but the foregoing figures may be taken as indicating the magnitude of the changes to be expected in the case of any soil as the moisture content varies.

The importance of the effect of moisture is thus made apparent. A difference of a few per cent makes a very marked difference in the effectiveness of ground connections made with electrodes of limited extent, especially at low values; that is, 15 per cent or less. Hence, every effort should be made to select locations for ground connections where the greatest amount of moisture is to be obtained; that is, if there is any choice in the matter. Many cases will arise where waste water of some kind can be utilized to good advantage.

[30] Technologic Paper No. 25, Bureau of Standards, Electrolytic Corrosion of Iron in Soils.

(*c*) Experimental Results.—In order to determine the seasonal variation of resistance of earth connections which might be expected under the climatic and soil conditions prevailing in the vicinity of Washington, measurements were made at intervals of one month for about a year and a half on the specimens already described in this paper. These specimens, it may be repeated, consisted of driven pipes, plates, strips, and a number of patented devices. The ground in which the tests were made is a rather stony clay, which has been found by measurement to be of somewhat higher resistivity than most of the soils met with in other localities, although the soil in some places will be of even higher resistivity and, hence, worse for the purpose of making ground connections. The measurements were made by the ammeter-voltmeter method.

The results of measurements on a number of specimens representative of each type are shown plotted in Figs. 21, 22, and 23. Where more than one specimen of each kind was available, the average resistance is given. As would be expected, the maximum resistance for nearly all of the specimens occurs in midwinter and the minimum in midsummer. The average total change is seen to be about 70 per cent. In particular, for 0.75-inch pipe 3 feet long the maximum is 1.7 times the minimum; for 0.75-inch pipe 10 feet long, 1.4 times; for strips 20 feet long, 1.8 times; for a plate 2 by 8 feet, 1.7 times; for Paragon ground cones, 1.7 times; Maxum ground boxes, 1.6 times; Brach hydrogrounds, 1.6 times; Lord Manufacturing Co. hydrogrounds, 1.9 times; and Federal Sign System cartridge ground plates, 2 times.

With the exception of Nos. 8 and 9, Fig. 23, there seems to be no material increase of resistance with time. In fact, it may be considered that there has been an improvement in the condition of the ground connections, because the resistances of January, 1915, are practically the same as of January, 1916, although on the latter date the soil was drier than on the earlier date, and the temperature about the same. With Nos. 8 and 9, however, the case is different. These specimens show a marked increase of resistance during the course of the year. On the other hand, it is seen that in several cases there was a marked decrease of resistance during the first month after the measurements were begun. This is largely due to the fact that holes were dug and allowed to stand open for several days before the electrodes were buried. When the holes were filled the metal was surrounded

by soil which had been more or less dried by exposure to air so the resistance to flow of current was at first rather high in comparison with values obtained later.

In making the measurements mentioned above, it was necessary to determine each time the resistance of a ground connection made to the city water system. The conductor leading to the water main consisted of 250 feet of enameled steel conduit in series with a long service pipe. The conduit was laid underground with joints which had been screwed together after being daubed with a mixture of red lead and oil. The total resistance of this ground connection was found to be about 1.7 ohms, of which ap-

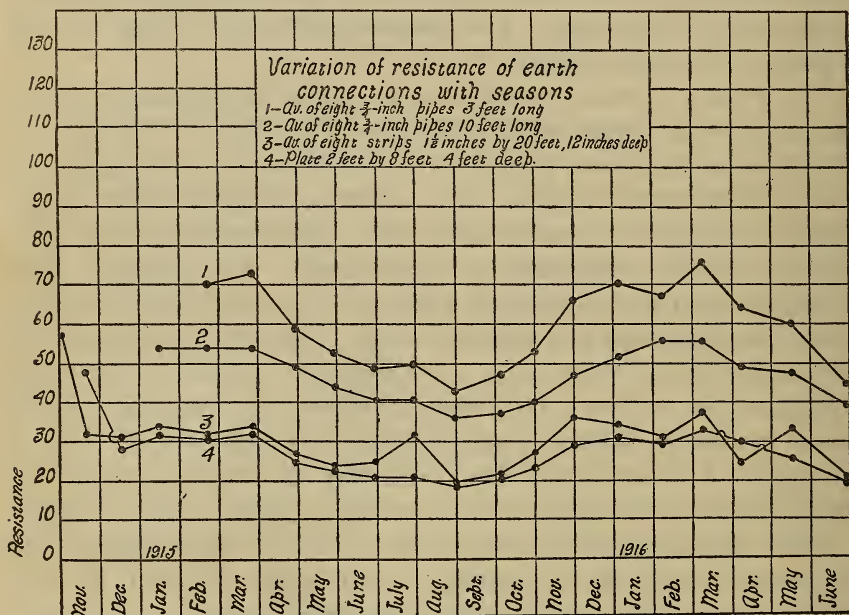

FIG. 21

proximately 1 ohm was found to be in the conduit. The remaining 0.7 ohm was the resistance offered by the service pipe and water main. Measurements each month showed no variation of resistance with time that could not be attributed to errors in measurement.

It should be noted in connection with these tests that there was but little freezing weather and most of the time the soil was fairly moist, and at times, especially in January, 1915, very wet. There were no extremely cold or dry periods. The only dry periods of any consequence occurred just before the measurements made at the end of March and at the end of July in 1915. Preced-

ing the measurements at the end of August there was much hot weather with several heavy rains, 3.32 cm (1.31 inches) of rain falling on August 30. On August 31 the lowest recorded resistance for the year was obtained. Following August the precipitation was light, with the exception of one or two hard rains in October, and the temperature decreasing, so the resistances increased steadily.

Other data showing the seasonal variation of resistance of earth connections have been published by Hayden [31] from tests made on some driven pipes. These pipes were 3.75, 2.75, and 3.1 feet in length, respectively. Measurements were made on them at

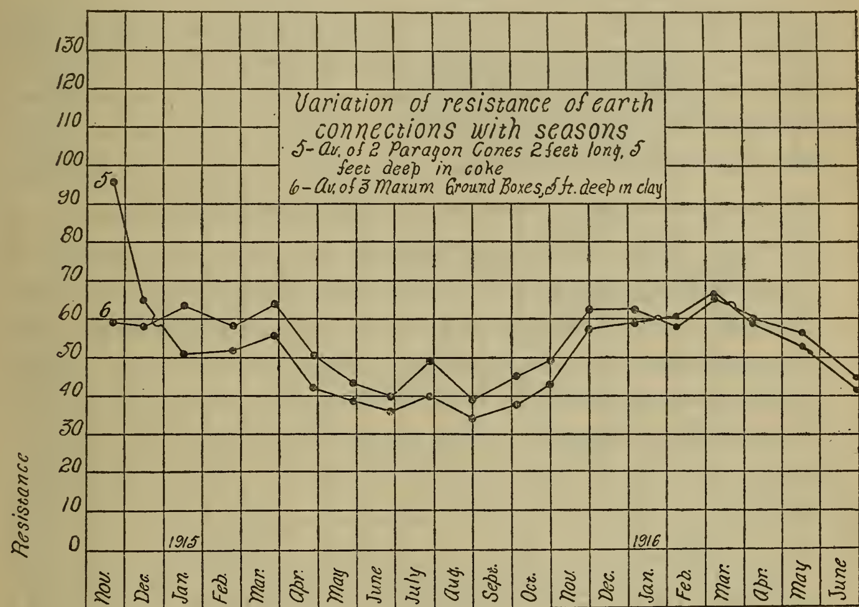

FIG. 22

regular intervals over a period of three years. The curves correspond to those described in the preceding paragraph in so far as the time of maximum and minimum values of resistance are concerned, the maximum value occurring in February and March and the minimum in July and August; but the differences between maximum and minimum values were found to be much greater than in the present investigation. In the case of one specimen, the maximum was three times the minimum, and in another seven times the minimum. This was probably due to deeper frost in the wintertime. Some of the curves given by Hayden are much more in detail than those in Figs. 21, 22, and 23 and

[31] Trans. A. I. E. E., 26, Pt. II, p. 1209.

show the variation from day to day. Curves showing the variation from day to day are of a saw-toothed form, because a heavy rain or a few dry days produce considerable abrupt changes. As shown by Hayden's curves, these in some cases may be as much as 20 per cent in two or three days, but they are not important. It is the large changes from season to season that are of real significance.

It is obvious, of course, that measurements such as those described above can be taken only as indicating the magnitude of the changes that may be expected in the particular locality in which they are made. These changes will be different for different soils

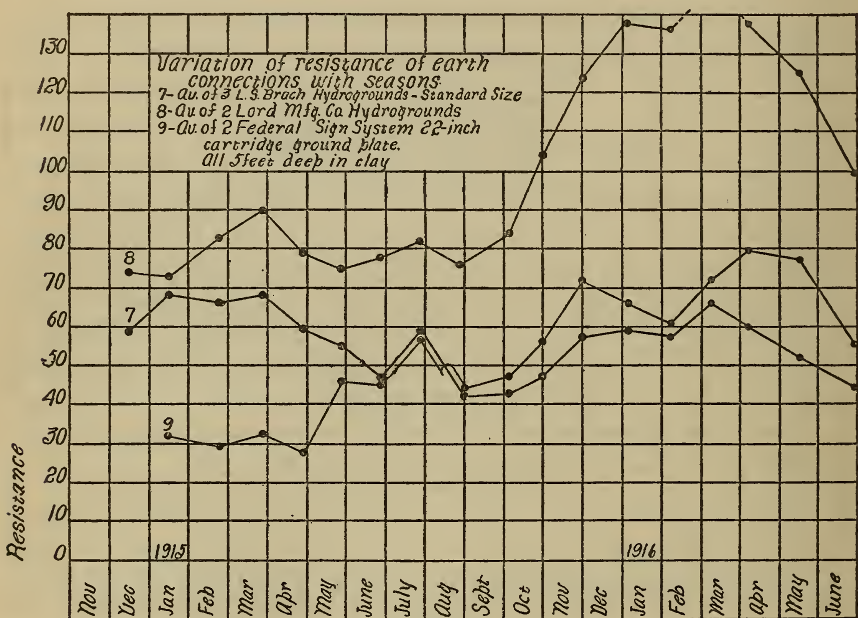

Fig. 23

and for different climatic conditions. They may even vary widely from year to year for the same locality. Thus, a very cold winter followed by a hot summer with heavy rainfall would produce an exceedingly great change in the resistance, whereas a mild winter followed by a dry summer might show nearly uniform resistance throughout the year. Moreover, with a given variation in temperature and rainfall, the soil conditions have great influence; for if the soil is of fine texture with bedrock at a great depth, moisture is accumulated in wet seasons and retained to a greater or less extent in dry seasons, which tends to produce a uniform value of resistance from season to season. On the other hand,

with soil of a loose sandy or gravelly nature, moisture is not retained so readily, and large fluctuations of resistance may be expected. With bedrock near the surface of the ground, large variations of resistance may also be expected whatever the nature of the soil, because evaporation rapidly exhausts the supply of moisture which can be stored in wet seasons in the thin layer covering the rock. Ordinarily the depth at which ground connections are placed—that is, within practical limits—also has some influence on changes in resistance. This, in some cases, may be considerable, and in others it may be negligible. In the measurements described above it will be noted that in the case of driven pipes 3 feet long the maximum was 1.7 times the minimum, while in the case of pipes 10 feet long the maximum was 1.4 times the minimum. Generally the deeper a ground connection is the more uniform its resistance is likely to be. In passing, it should be emphasized again that the foregoing remarks apply more particularly to ground connections made with electrodes of limited extent.

8. INCREASING THE CONDUCTANCE OF GROUND CONNECTIONS

As indicated heretofore in this paper, the normal resistivity of the soil in most localities is such as to make the resistance of a ground connection made with an electrode of limited extent rather high. In such places ground connections of low resistance can be made by placing a sufficient number of electrodes in parallel, but this requires considerable space and is expensive, especially if the resistance required is comparable with that of ground connection made to a water pipe. In order to lessen this difficulty an expedient has been many times resorted to, which is that of reducing the resistivity of the soil immediately surrounding the electrode, thus enabling the attainment of a low resistance with a much smaller number of electrodes than would otherwise be the case. To reduce the resistivity of soil it is only necessary to dissolve in the moisture normally contained in it some substance which is highly conducting in its water solution. There are many substances which could be used for this purpose, but most of them are expensive or are otherwise unsuitable. The substance most often used is salt ($NaCl$). Another which could be used to greater or less advantage is calcium chloride ($CaCl_2$). Both are highly soluble in water, are highly conducting in solution, and are comparatively cheap. The ratio of the conductivities of solutions of these substances to that of ground water may be stated to be of the order

of 1:100. They possess disadvantages, however, in that they are more or less corrosive, at least toward iron, and their effects are not permanent. The supply of salt must also be renewed at intervals to replace that washed away by water percolating through the soil.

Another method of increasing the conductance of ground connections, especially buried plates, is that of surrounding the electrode with charcoal or coke. It is thought by many that this method presents distinct advantages, but others discredit it. Experiments by Sloss and Fish,[32] for instance, do not show that the addition of charcoal reduces the resistance of a ground connection, and experiments by Ford [33] point to the same conclusion. In both of these investigations it was also found that ground connections made in this way vary in resistance with seasons and increase in resistance with age to a greater extent than ground connections made without these substances. In fact, all of the results obtained seem to indicate that either charcoal or coke is more of a disadvantage than a help. This experience is not reported from other quarters, however, and it may be that the instances cited above are exceptional. At any rate the idea is prevalent in many places that a good ground connection can not be made without using one or the other. Their effects in reducing the resistance of a ground connection have been attributed by some to their power of attracting and absorbing moisture, which is stated to tend to lower the resistance to flow of current away from the electrode into the earth. Whether this is the case is open to question. It seems more likely that a view held by others more nearly represents the facts. This view is that the highly conducting coke or charcoal has an effect equivalent to that produced by increasing the surface area of the electrode in contact with the soil.

In order to determine some of the effects of salt and coke, and more particularly the time required for rain water seeping through soil to wash the salt away, several specimens were buried and measurements of resistance made on them at intervals of one month for about a year and a half. A discussion of the results of these experiments, and also the results of some measurements of the resistivity of samples of soil containing different quantities of salt, is given below.

(*a*) Effects of Salt.—To obtain an idea of the time required to eliminate the effects of salt by percolation of moisture through

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[32] Electrical World, 55, p. 1134.

[33] Electrical World, 58, p. 622.

soil two specimens were buried, one consisting of a strip of No. 20 gage galvanized sheet iron 1.5 inches wide and 60 feet long, and the other of a plate of No. 16 gage galvanized sheet iron 2 by 8 feet. The strip was buried in a trench 12 inches deep with 1 pound of salt per foot of strip. The plate was buried in a hole 4 feet deep, with 74 pounds of salt. The soil, as before stated, was a rather stony clay of fine texture.

The results of the monthly measurements of resistance have been plotted in Figs. 24 and 25, curves (3) and (6). In both cases results obtained on similar specimens buried in clay without salt are also shown to aid comparison. In the case of the

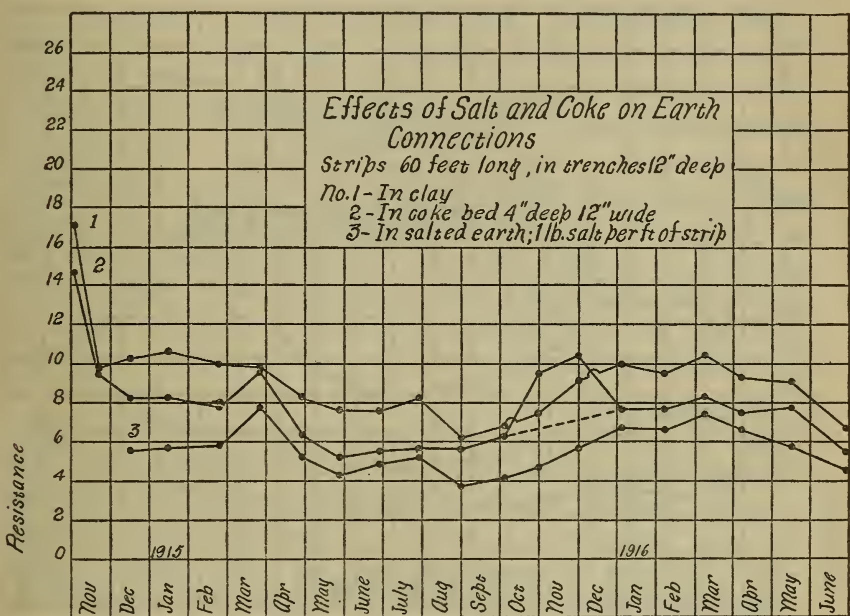

FIG. 24

strip, the addition of the salt appears to have reduced the resistance by about 30 per cent. This is somewhat less than would be expected. There is, however, no way of telling what the resistance would have been if the strip had been buried in the same trench without salt, and it may be that curve (3) under those conditions would be considerably above curve (1). This supposition is strengthened by the fact that measurements made on other specimens indicate the resistivity of the soil in the vicinity of the specimen from which curve (1) was obtained to be lower than elsewhere. The apparent reduction of 30 per cent is therefore undoubtedly to be considered as rather small. On

the other hand, in the case of the plate, the reduction of resistance is about 75 per cent. In addition, the specimens from which curves (4) and (6) were obtained were only about 20 feet apart, and nothing developed in the course of the measurements which would suggest that there was much difference in the resistivity of the soil in the two places. The reduction shown may therefore be taken as indicating the actual change caused by the salt.

The most important fact brought out by these tests is that of the lasting effect of an application of salt, for there appears to be no permanent increase of resistance of either the strip or the plate during the period covered by the measurements. More-

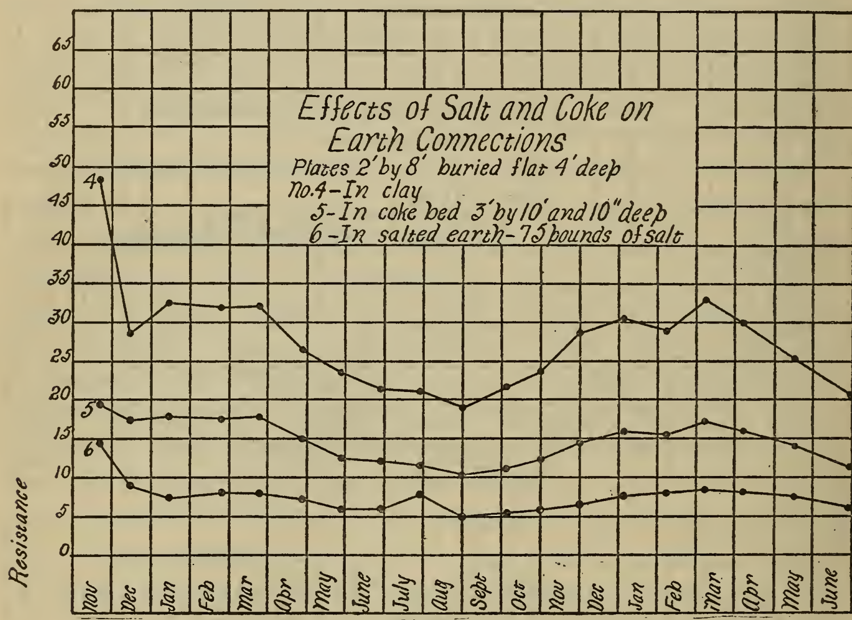

FIG. 25

over, the precipitation during this period was close to normal, the records of the Weather Bureau showing the actual precipitation from November 1, 1914, to January 31, 1916, to be 47.78 inches, and the normal precipitation to be 52.74 inches. The rate of washing away of the salt may therefore be considered as being practically as rapid as during a similar period of normal precipitation. Hence, it is not likely that with soil of the kind in which these ground connections were made, the salt would have to be renewed oftener than once in two years. This soil, however, is of close texture. In soils of loose texture, percolation of moisture from the surface downward would be more rapid during

rainfall, and salt would be carried away at a greater rate; and when once carried to a considerable depth in loose soil the tendency for the solution to return by capillary action during dry seasons would be much less than in soil of close texture. Consequently, the salt would have to be renewed oftener than in soils through which water does not pass so readily, but to state definitely the length of time between renewals in any case would require further experiments.

A question which arises is that of the amount of salt to be used to produce the best results from a ground connection. To obtain some information on this subject, 12 samples of dry red clay were prepared by adding water until the contained moisture amounted to 30 per cent by weight of the dry earth, and salt (NaCl) in different proportions to each sample until the moisture in the different samples formed solutions ranging in strengths from 0 to 16.6 per cent by weight of the water. The salt was dissolved in the water and the resulting solution and earth thoroughly mixed, after which the samples were placed in air-tight glass jars and allowed to stand two days for diffusion of the solution to take place. The resistivity of each sample was then measured by tamping it into a glass-lined cylinder with an iron bottom, forcing an iron piston down upon it, and using alternating current at 60 cycles per second with an ammeter and voltmeter. The results of these measurements are shown plotted in Fig. 26. It is there seen that the addition of 0.33 per cent of salt to the contained moisture causes the resistivity to drop from 4100 ohms per cubic centimeter to about 700 ohms per cubic centimeter. At this point the rate of decrease of resistivity with increase in the percentage of salt in the moisture becomes much slower but is still considerable, and with the moisture containing 16 per cent salt the resistivity is about 55 ohms per cubic centimeter. After 10 per cent is reached, however, further additions of salt produce but slight changes in resistivity, at least as compared with the changes produced by the first small additions.

In making this test a record was kept of the volume and weight of the earth used, the volume being taken as that of the tamped earth when ready for the resistivity measurements. The weight of the dry earth was found to be about 90 pounds per cubic foot. The moisture content of soils ranges from about 15 per cent in dry seasons to 35 or 40 per cent in wet seasons, so the weight of the contained moisture ranges from 13.5 to 36 pounds per cubic

foot. From the curve of Fig. 26 it is seen that if enough salt is dissolved in the moisture to make of it a 0.5 per cent solution, the resistivity of the soil will be reduced to about 14 per cent of its normal value. To produce this result with 40 per cent moisture in the soil would therefore require the addition of about 0.18

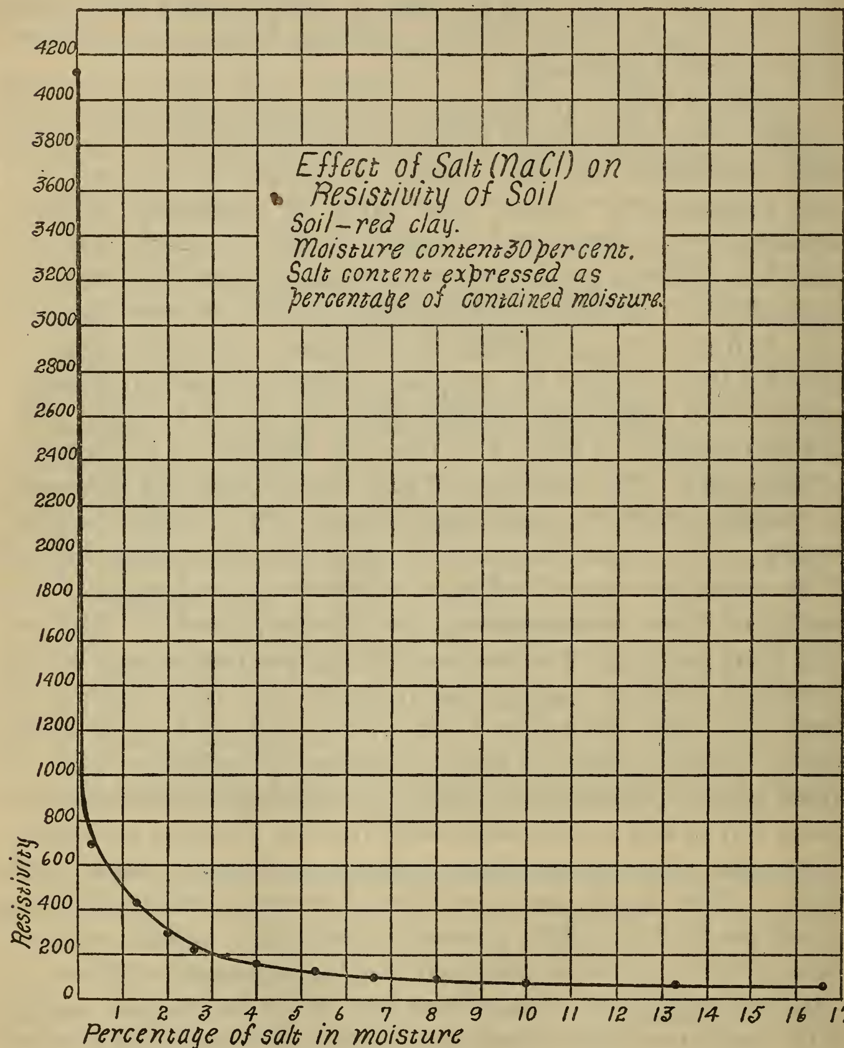

Fig. 26

pound per cubic foot of earth; to reduce the resistivity to 10 per cent of its normal value would require the addition of 3 times as much, to 5 per cent of its normal value 6 times as much, and so on.

From these data may be obtained an idea of the quantity of salt required to produce large reductions in the resistance of

a ground connection. With an electrode of any shape, the production of large changes would necessitate the addition of salt to all of that portion of the surrounding earth which contributes in any considerable measure to the resistance to flow of current. For example, let a pipe driven in soil of fairly uniform resistivity be considered. As will be shown later, if current is flowing away from such a pipe into the earth, approximately 90 per cent of the total difference of potential between the pipe and a point in the earth a great distance away occurs in a region within 6 feet of the pipe. Hence, if to the water contained in a cylinder of earth 12 feet in diameter and extending some distance below the bottom of the pipe enough salt were added to make of it a 0.5 per cent solution, the portion of the total resistance contributed by this cylinder would be reduced to 14 per cent of its normal value. If the total resistance were originally 25 ohms, the resistance after being salted as described above would be about 5.6 ohms, for that part of the soil contributing 10 per cent of the original resistance would be unaffected, while the remainder, or the portion contributing 22.5 ohms, would be so affected that its resistance would be reduced to 3.15 ohms, the sum of the components then being 5.6 ohms. If the pipe were 10 feet in length, the cylinder of earth 12 feet in length and containing 40 per cent of moisture, the weight of salt required would be 245 pounds, since the volume of the cylinder is 1360 cubic feet.

By increasing the quantity of salt a still further reduction of resistance could be effected. If salt were added until the contained moisture become a 10 per cent solution the resistivity of the soil would be about 1.87 per cent of its normal value. The total resistance of the earth connection would then be about 2.9 ohms. This, however, would require 20 times as much salt as in the case described in the preceding paragraph, or about 5900 pounds, and the added reduction would not be worth the added expense. The same result could be accomplished for less than half the cost by driving two pipes 10 feet apart and using but a fraction of this amount of salt. In fact, in any case where a ground connection of a given resistance must be made, especially if the resistance required is very low, maximum economy will probably lie in the use of several electrodes combined with an amount of salt which will not be a source of excessive expense for renewals.

Nevertheless, the foregoing data indicate that a more liberal use of salt than has heretofore been the general practice is desir-

able. In the past it has been considered by many that when a few pounds of salt had been added all had been done that could reasonably be expected. But it is obvious from what has been said above that several hundred pounds could be used to advantage with earth connections that are of importance, and where low resistance is necessary, and for earth connections of almost any kind a hundred pounds would not be too large an amount.

Moreover, with a liberal use of salt an advantage aside from that of reduction of resistance is obtained, although it is much less than has sometimes been stated to be the case. This is in an increased uniformity of resistance; that is, alternate dry and wet or hot and cold seasons make smaller proportional changes in salted ground connections than in those that are unsalted, or are made with charcoal or coke. Referring to Fig. 26, it is apparent that if the moisture around an earth connection contained enough salt to form a 0.5 per cent solution at a moisture content of 40 per cent, a reduction of the moisture to 20 per cent would increase the concentration of salt and hence decrease the resistivity of the solution to an extent sufficient under some conditions largely to counteract the effect of the drying. For instance, measurements of the resistivity of soil containing different percentages of moisture show that changing the moisture from 40 to 20 per cent changes the resistivity by about 30 per cent.[34] Doubling the concentration of salt produces practically the same change in the opposite direction, so the two tendencies would almost exactly counteract each other. With further drying, however, the rate of increase of resistivity with decrease of moisture becomes much more rapid, and, on the other hand, with increasing concentration of salt the decrease of resistivity becomes slower, so the effect of the salt in producing uniformity of resistance become less with increasing dryness of the soil.

With regard to minimizing the effects of changes in temperature salt is probably of most service in lowering the freezing point of the solution, thus putting the point of sudden large increase in the resistivity of soil several degrees below the freezing point of water. The relative importance of the effect of salt in producing uniformity of resistance is apparent on examination of Fig. 25, where it is shown that the ratio of maximum to minimum resistance is about 1.4 for the plate put down with salt and 1.7 for the plate put down without salt.

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[34] Technologic Paper No. 25 of the Bureau of Standards, p. 57.

(*b*) Effects of Coke.—In order to obtain some information as to the extent to which coke may be depended upon to reduce the resistance of ground connections two specimens were put down, one of which consisted of a strip of No. 20 gauge galvanized sheet iron 1.5 inches wide and 60 feet long. This strip was buried in a trench 12 inches deep, with a bed of coke filling the trench to a depth of 4 inches and of the same width as the trench which was about 12 inches. The other specimen was a plate of No. 16 gauge galvanized sheet iron 2 feet wide by 8 feet long, which was buried flat in a hole 4 feet deep, with a bed of coke filling the hole to a depth of 10 inches. The area of the coke bed was about 3 by 10 feet. An attempt was made to place the coke as nearly uniformly about the electrodes as practicable.

The results of the periodical measurements of resistance have been plotted in Figs. 24 and 25, curves (2) and (5). Curves from specimens buried in clay are also given to aid comparision. In the case of the strip, as shown by curve (2), there is some reduction of resistance, but apparently not nearly as much as for the strip put down with salt. Moreover, the variation of resistance from time to time is obviously as great as in curve (1), although the high values noted on November 1 and December 1, 1915, are undoubtedly to be attributed to a loose lead. At any rate, on January 4, 1916, the lead was found detached from the strip and another substituted for it, so the dotted line connecting the points representing the values of resistance obtained on October 4 and January 4 probably nearly represents the actual resistance. In the case of the plate, on the other hand, the reduction of resistance is much greater than in that of the strip, being about 53 per cent, but with regard to uniformity of resistance the effect of the coke does not appear to be more marked here than above, since the ratio of maximum to minimum is 1.7, or the same as for the plate put down in clay.

Measurements made on the coke used in the experiments just described show its resistivity to be of the order of 130 ohms per cubic centimeter, or but a fraction of that of the average soil. This value was obtained on a sample that had been in the ground for more than a year. It was dug up, pounded fine in a mortar, tamped in a glass-lined iron cylinder in the same way as described for tests of the effect of salt on the resistivity of soils, and its resistivity measured with alternating current. It was then dried and its resistivity measured again, the result being practically the same. The resistivity was found to vary between wide limits with pressure and temperature, so the coke in the two conditions

was measured at as near the same temperature and pressure as practicable. The pressure was applied by means of a metallic piston, and was about 14 pounds per square inch. The temperature was a little higher than that of the room, which was 21° C, on account of the heating effect of the current which was allowed to flow for a short time before the readings were taken. The values obtained are to be considered only as showing that the resistivity of coke is very low in comparison with that of the soil, and that the difference in conductivity between wet and dry coke amounts practically to nothing.

When the resistivity was measured, the moisture content was also obtained, and found to be about 19 per cent, by weight, of the dry coke. The soil in which the sample was buried seemed to be quite saturated and must have contained more than 30 per cent moisture. The coke, therefore, had ample opportunity to become saturated. The weight of the packed dry coke was 70 pounds per cubic foot. The weight of the water per cubic foot of wet coke was 12.2 pounds. It was noted that the volume of the coke when dry was less than when wet. The shrinkage on drying was from 31 to 28.5 cubic inches, the volume in both instances being measured when packed and under pressure for the resistivity measurements. The total amount of water driven off was 0.22 pound.

From these data the function of the coke in reducing the resistance of ground connections is readily apparent. It is that of replacing a volume of earth of high resistivity surrounding the electrode with an equal volume of coke of low resistivity. The greater the volume of coke the greater the reduction of resistance, although not in the same proportion. Whether the coke is wet or dry makes but little difference. Moisture changes, in affecting the resistance of ground connections made with coke, act only on that part of the resistance contributed by the soil, but because the portion of the total resistance contributed by the soil is large in comparison with that contributed by the coke the effects appear to be practically as great, in percentage at least, as in ground connections made in clay. For example, take an electrode in earth having a resistivity of 5000 ohms per cubic centimeter which shows a resistance of 25 ohms to flow of current away from it. If enough coke is placed around it to reduce the resistance 40 per cent, the resulting resistance will be 15 ohms. Since the ratio of resistivities of coke to soil is about as 1:40, the portion of the resulting resistance contributed by the coke is about one-fortieth of that contributed by the earth which it replaces, or

0.25 ohm. The portion of the 15 ohms contributed by the soil is therefore 15 −0.25 =14.75 ohms. Hence, moisture changes produce practically as large percentage changes as if the coke were not present. On account of its low resistivity, the coke bed constitutes virtually an extension of the electrode, and its distribution is for that reason of considerable importance. For the best results it should have a large area of contact with the soil in proportion to its volume.

The foregoing results do not agree in every respect with those of Sloss and Fish, and Ford, previously mentioned, but they do indicate that the benefits derived from the use of coke are not as great as has sometimes been stated to be the case. For instance, particular stress has been laid by some upon the uniformity of resistance obtained, but this statement is not supported by the tests because ground connections made with coke are seen to be almost as sensitive to changes in moisture conditions as those made in clay. There is, of course a considerable reduction of resistance, although this advantage is offset in large measure, at least, by the fact that it is in all cases necessary to excavate to get the coke in place. And in this respect it is at a disadvantage as compared with salt, which can be carried into the ground by burying it near the surface and flooding the hole with water, or allowing time enough for seepage of rain water to accomplish the same purpose. Coke and charcoal, however, do not have to be renewed, and in this respect present an advantage over salt.

The greatest disadvantage attending the use of either coke or salt is that touched upon in a previous paragraph, viz, an increased rate of corrosion of the electrode and consequent shortening of the life of the earth connection as compared with its life in normal soil, especially where galvanized iron is used. Just what this reduction in life may be can not at present be stated because of lack of data. In fact, experiments extending over several years would be necessary to obtain the desired information, but there seems to be no doubt in the minds of many that the reduction in life is considerable, coke in general being considered more detrimental than salt. Others state that the effects of salt on galvanized iron underground are negligible. In this connection it should be mentioned that the specimens described above showed no appreciable corrosion on superficial examination after being in the ground 14 months. Nevertheless, it is likely that the increase of corrosion due to the presence of salt will be considerable in its effects over a period of years, resulting in a material shortening

of the total life of the earth connection; and, moreover, the effects of coke may well be anticipated to be greater than those of salt. Copper, on the other hand, is much more resistant to corrosion than galvanized iron, and where long life of an earth connection with little attention is much to be desired copper should undoubtedly be used.

9. DISSIPATION OF ENERGY BY GROUND CONNECTIONS

For successful operation ground connections must in some cases be able to dissipate considerable amounts of energy without material changes in their resistances. An instance is afforded by an accidental contact between a high-voltage and a low-voltage circuit. Here the conditions may be such that the current flow through the ground connection is insufficient to operate the protective devices, and if it is it may continue almost any length of time before it is detected and the fault removed. In the meantime the rate of liberation of energy in the soil in the form of heat is proportional to I^2R, I being the current and R the resistance to its flow away from the electrode. A large part of this heat is absorbed by the soil water, and it is obvious that if the rate of its liberation at any point is high enough steam will be formed there and moisture thus driven into the neighboring soil or the atmosphere. An excessive current, therefore, is likely to cause drying of the earth immediately surrounding the electrode and a consequent great increase of resistance.

In the course of this investigation some experiments were conducted in collaboration with the Potomac Electric Power Co., of Washington, D. C., which show the behavior of ground connections when subjected to a greater rate of liberation of energy than they can continuously care for. These experiments were made on five specimens of 0.75-inch galvanized-iron pipe driven to a depth of about 10 feet in soil consisting of a fill containing cinders, ashes, and other refuse. They were put down by first driving a pointed 2-inch pipe to a depth of about 5 feet, pulling it out, and driving the smaller pipe in the bottom of the hole. Before driving the smaller pipe, however, about 2.6 gallons of 15 per cent salt (NaCl) solution was poured in. The resistances were measured and found to be as follows:

TABLE 10

No. of specimen	1	2	3	4	5
Ohms	12.4	11.2	15.4	7.6	16.7

In the first set of experiments 1100 volts were impressed upon Nos. 1 and 4 in series. The current at the beginning was 61 amperes. At the end of five minutes No. 1 began to steam. It soon stopped, however, and No. 4 commenced. At the end of 16 minutes the current had decreased to 24 amperes, with the greater part of the energy being consumed by No. 4. The soil nearest the pipe glowed and gave off clouds of smoke, due most likely to burning humus. A measurement of voltage between the pipe and a spot on the ground about 1 foot away showed a difference of potential of 885 volts. A similar measurement on No. 1 showed a difference of potential of only 30 volts. The current fluctuated with great rapidity after the earth connection began to smoke, making accurate measurements very difficult. Two or three buckets of water were poured on the ground around No. 4, but produced no permanent effect. At the end of the experiment the ground was flooded with water from a hose.

The following day the test on Nos. 1 and 4 was repeated. This time no disturbance occurred around No. 4, but within 10 minutes No. 1 began to steam, and in 52 minutes the current had decreased from 80 to 30 amperes. The soil immediately surrounding the pipe finally glowed and gave off clouds of smoke in the same way as described for No. 4 in the preceding paragraph. The current in No. 1 was then discontinued, and Nos. 4 and 5 connected in series. In 36 minutes No. 5 began to smoke, and the current had decreased from 35 to 4 amperes. At the conclusion of this series of experiments about 6.6 pounds of salt was buried in the soil around each specimen.

Three months later a similar test was made on Nos. 1 and 5, immediately following a heavy rain. A current of 60 amperes at 1100 volts was maintained for 40 minutes, but no increase of resistance became apparent, although No. 5 gave signs of failure by steaming. The circuit was broken at the end of 40 minutes to avoid overheating of the transformers. The effect of the salt and the increase of moisture due to rainfall is made evident by the resistances, measured before beginning the test, which show a marked decrease from the values obtained at the time of the first experiment, and were as follows:

TABLE 11

No. of specimen	1	2	3	4	5
Ohms	6.42	6.50	8.80	3.83	11.4

The most obvious fact brought out by these experiments is that mentioned above, viz, that if a ground connection is required to dissipate energy at an excessively high rate drying of the soil will occur, with a great increase of resistance. But this increase of resistance is not permanent; the original conductance is recovered in a short time. In addition it is apparent that the relative capacities of ground connections to dissipate energy are not reliably indicated by their resistances, at least not for electrodes of the same size and shape. For as indicated in the first experiment, No. 4 was first to fail, although its resistance was only a little more than half that of No. 1. Finally, the magnitude of the rate at which a ground connection of the dimensions of those described above can dissipate energy continuously without an increase of resistance may be estimated from the results of the last test. The current was 60 amperes, the resistance of No. 1 at the start 6.42 ohms, and of No. 5, 11.4 ohms. Hence, the value of I^2R for No. 1 is about 23 kw and for No. 5 about 41 kw. The latter gave signs of failure, but as far as could be told No. 1 would have carried 60 amperes indefinitely. It is possible, however, that after a number of hours an increase of resistance would have taken place. On the other hand, several tests showed that dissipation of energy at a rate of 3 to 5 kw produced no effect on any of the specimens beyond a slight decrease of resistance due to increase of temperature. It appears, therefore, that it may safely be assumed that the maximum rate at which a ground connection made by driving a pipe to a depth of 10 feet in moderately salted moist soil can dissipate energy continuously without an increase of resistance lies somewhere between 5 and 20 kw. Nevertheless, if there is a possibility that a ground connection of this kind will ever have to dissipate energy at a rate of more than 8 or 10 kw it is perhaps best that an investigation be made to determine whether it will meet the requirements.

The probable reason why the capacity of a ground connection to dissipate energy is limited appears from the following considerations: When current is flowing the rate of liberation of heat is, in general, greatest in the layer of earth nearest the electrode, for it is there that the current density is greatest, and the rate of liberation of heat varies as the square of the current density. As a consequence water evaporates more rapidly from this layer than elsewhere, and, if it is not replaced at a rate equal to that

at which it is driven away, drying of the soil will follow, causing an increase of resistance. On the other hand, if it is replaced at the same rate as it is driven away current can flow indefinitely without an increase of resistance. Now, the only way in which the evaporated moisture can be replaced is by water flowing in from the surrounding region by capillary action. This, of course, takes place, but there is a definite limit to the rate at which water can move through soil by this means. Hence, if the current flow through a ground connection is gradually increased, a point will ultimately be reached at which heating drives off moisture faster than it is supplied, with results as described in the preceding paragraphs.

No tests have been conducted on ground connections consisting of electrodes of different forms under different conditions, but it is readily apparent that the maximum capacity of a ground connection made with an electrode of any form to dissipate energy may differ widely with the kind of soil in which it is situated, and also vary from time to time for the same soil. Among the factors which affect it may be named the moisture content, the rate at which moisture moves by capillary action and the distance which it will cover, the surrounding temperature, and the size of the electrode. It is practically impossible to separate some of these various factors, or control them experimentally, and for that reason laws or performance records under a variety of conditions from which the maximum capacity of a ground connection to dissipate energy may be predicted with any degree of exactness are not readily obtainable. If this characteristic of a ground connection must be known it is nearly always necessary to make a test in each case. It may be stated, however, that the greater the moisture content of the soil the greater the rate at which energy can be dissipated. Moreover, with a given moisture content, this rate will be greater in soils of fine texture than in those of coarse texture, because the former carry moisture at a greater velocity and over greater distances by capillary action than the latter. The surrounding temperature may also produce a marked effect, for the lower it is the greater the rate at which heat will be carried away by radiation and conduction.

With regard to the size of the electrode, it is easily demonstrated, for certain special cases at least, that the larger it is the greater the rate at which energy can be dissipated without too

rapid evaporation of moisture. In order to do this suppose an electrode of any shape to be buried in the ground. Let

A_1 be the surface area of this electrode in contact with the soil,
R_1 the resistance to flow of current away from it,
I_1 the total current, and
i_1 the average current density.

The rate of dissipation of energy will be $I_1^2 R_1$.

Suppose the dimensions of the electrode to be increased. Let

A_2 then be the surface area in contact with the soil,
R_2 the resistance to flow of current,
I_2 the total current, and
i_2 the average current density.

If the rate of dissipation of energy in the two cases is the same, $I_1^2 R_1 = I_2^2 R_2$ . . . . (*a*). Evidently $i_1 A_1 = I_1$, and $i_2 A_2 = I_2$. Substituting in (*a*), $i_2 = i_1 \frac{A_1}{A_2}\sqrt{\frac{R_1}{R_2}}$.

Now, as mentioned heretofore, in the case of a circular plate embedded to a depth equal to one-half its thickness in the ground the resistance is $R_1 = \rho/2d$, where d is the diameter of the plate and ρ the resistivity of the soil. If the diameter is increased by a factor n, $R_2 = \rho/2nd$. Also $A_1 = \pi r^2$ and $A_2 = \pi n^2 r^2$. From (*a*), therefore, $i_2 = i_1 \frac{\sqrt{n}}{n^2}$, in which, since $n > 1$, the factor $\sqrt{n}/n^2$ is always less than unity, and $i_2 < i_1$.

In the case of a driven pipe, $R_1 = \dfrac{\rho \log_\epsilon \frac{2L}{d}}{\pi L}$, where L is twice the length of the driven pipe, and d its external diameter. If the length of the pipe is increased by a factor n, $R_2 =$

$$\frac{\rho \log_\epsilon \frac{2nL}{d}}{\pi n L}. \quad \text{Also } A_2 = nA_1.$$

$$\therefore i_2 = i_1 \sqrt{\frac{\log_\epsilon \frac{2L}{d}}{n \log_\epsilon \frac{2nL}{d}}}$$

Here, since $n > 1$, the denominator of the fraction under the radical, is greater than the numerator, so the value of the fraction is always less than unity. Hence $i_2 < i_1$.

In the case of a buried strip, as shown by measurements previously discussed, increasing the length causes practically a propor-

tional inverse change in the resistance. That is, if the length is increased by a factor n, it follows that $A_2 = nA_1$ and $R_1 = nR_2$. Whence $i_2 = i_1\sqrt{n}/n$ and $i_2 < i_1$.

It appears, therefore, that an increase in the size of an electrode, at least of those shapes commonly used in practice, results in a decrease of the average current density for the same rate of expenditure of energy. And, since the rate of liberation of energy in the form of heat at any point is proportional to the square of the current density, the tendency toward drying of the soil at the surface of the metal is diminished. Or, to put it in other words, an increase in the size of an electrode permits an increase in the rate at which energy can be dissipated without drying the soil and increasing the resistance.

In previous paragraphs the fact was mentioned that the rate of liberation of heat is greatest in the soil nearest the electrode, the rate being proportional to the square of the current density, and also to the resistivity. This being the case, if the resistivity is reduced by salting or otherwise, the capacity of the ground connection to dissipate energy will be increased, because the tendency toward drying of the soil at the surface of the electrode will be diminished. For example, take a driven pipe. A cylinder of earth 2 feet in radius and coaxial with the pipe may be estimated as contributing about 50 per cent to the total resistance. If a current is flowing, half of the total amount of heat will be liberated in this cylinder. Now, if the cylinder is impregnated with salt to a sufficient degree to make the resistivity one-fifth normal the portion of the total resistance contributed by it will be only 16.6 per cent instead of 50 per cent. Furthermore, if the same amount of heat is liberated as in the first case, the portion of the total liberated in the cylinder will also be 16.6 per cent instead of 50 per cent. Salting thus causes the distribution of heat liberation to be shifted in such a way that more of the heat is developed at a distance from the electrode than where salt is not used, with a consequent improvement in the facility with which it can be taken care of. Tests by Creighton [35] indicate that by thorough salting the capacity of an earth connection to dissipate energy may be increased by several times. The foregoing statement applies in greater or less degree to any treatment of the soil surrounding an electrode which decreases its resistivity.

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[35] General Electric Review, 15, p. 12 and 66.

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10. POTENTIAL GRADIENTS

When current flow takes place through a ground connection, a potential gradient exists in the surrounding surface of the ground. This potential gradient decreases on receding from the electrode and practically disappears at a distance of a few meters. It is of importance in that it may be a source of danger to persons and animals. In order to obtain data on its character in the vicinity of driven pipes when subjected to heavy current flow a test was made on some of the specimens previously described. This test consisted in passing a 60-cycle alternating current at constant

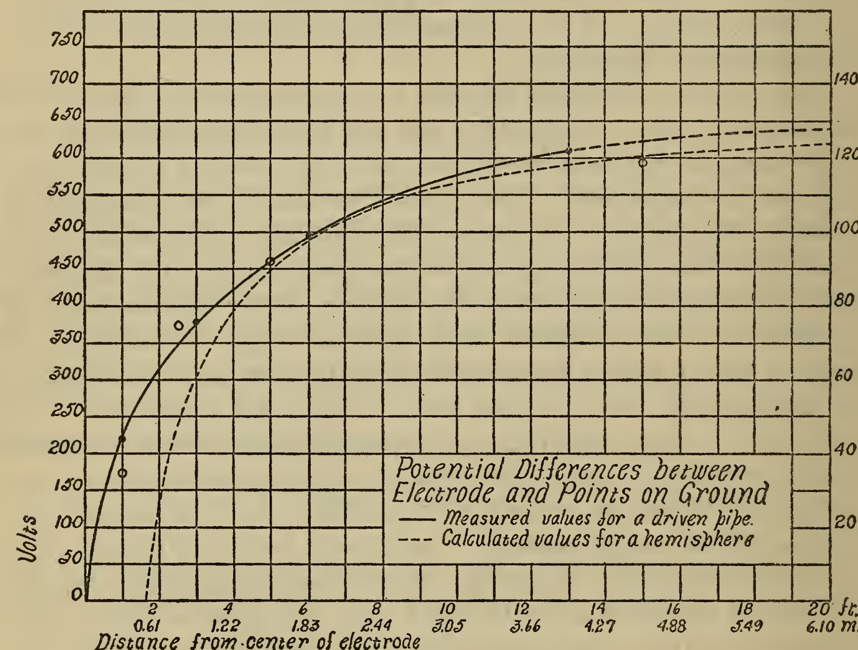

FIG. 27

voltage through the ground connection and measuring the potential differences between the pipe and points on the surface of the ground at various distances away. Plotting these potential differences as ordinates and distances as abscissæ gives a curve the slope of which at any point is proportional to the potential gradient. The results from a specimen which is more or less typical are shown in Fig. 27. This specimen is No. 1 of Table 10, Nos. 1 and 4 being in series in this particular case, with 232 volts impressed for one set of readings and 1100 volts for another. The total voltage was, of course, shared by the specimens very nearly in direct proportion to their resistances, since they were 104.5 feet

apart. Hence, the part taken by No. 1 can be calculated from the current and the resistance. The resistance was found to be 11.6 ohms, and the current at 12.5 amperes at 232 volts and 59 amperes at 1100 volts. The voltage impressed upon No. 1, therefore, was 143 in the first instance and 684 in the last. With the lower voltage the current was left on continuously, but with the higher voltage the current was allowed to flow only while readings were being taken to avoid change of temperature and a consequent change of resistance. Nevertheless, a slight change occurred, and there was a considerable change from the preceding day, for then, as shown in Table 10, No. 1 had a resistance of 12.4 ohms. In Fig. 27 the potential differences at the lower voltage are indicated by circles and refer to the scale at the right-hand margin, whereas the potential differences at the higher voltage are indicated by dots and refer to the scale at the left-hand margin.

For measuring the potential differences a double-scale voltmeter (0–150, 0–300) was used, and also a voltmeter (0–30) with a potential transformer. The resistance of the 150-volt coil of the voltmeter was 2044 ohms, and of the 300-volt coil 4083 ohms. The impedance of the high-voltage coil of the transformer, with the 0–30 voltmeter connected across the low-voltage terminals, was about 87 000 ohms. At each point of measurement some earth was loosened, water poured over it, and contact made with the ground by means of a brass disk, 7 inches in diameter, which was pressed into the wet soil.

The resistance to flow of current from the disk into the earth was not great enough seriously to interfere with the readings, that is, the reading recorded in each instance is not much less than the actual voltage. For, as shown below, the average resistivity of the soil appeared to be about 3600 ohms per cubic centimeter, and at the surface, on account of the admixture of coal dust, ashes, and other refuse, was probably less; 3000 ohms may be assumed as a fair value. Moreover, as indicated under resistance of ground connections, the resistance to flow of current away from such a disk is expressed by $R = \rho/2d$, where ρ is the resistivity of the soil and d is the diameter of the disk in centimeters. Hence, $R = 3000/2 \times 17.8 = 84$ ohms, a value which in this case can be neglected in comparison with the resistance of the voltmeter or the impedance of the transformer, since its effect on but few readings is sufficient to cause an error of as much as 4 per cent. In no

instance was difficulty experienced in repeating results with a fair degree of accuracy, especially at the higher voltage.

In Fig. 27 there is also plotted a curve showing potential differences calculated for a hemispherical electrode of a radius numerically equal to the combined electrostatic capacity in free space of the pipe described above (No. 1, Table 10) and its image, and embedded with its plane surface flush with the surface of the ground in uniform soil of the same resistivity as the average of that surrounding the pipe. The electrostatic capacity, and consequently the radius of the hemisphere, are seen from Table 1 to be 49.6 cm. The resistivity of the soil from $\rho = 2\pi CR = 2 \times 3.1416 \times 49.6 \times 11.6 = 3600$ ohms per cubic centimeter. The resistance to flow of current away from the hemisphere is therefore the same as for the pipe, or 11.6 ohms. Also, with 684 volts impressed the current will be 59 amperes. The potential differences may now be calculated as follows: Let r_1 be the radius of the hemisphere, in this case 49.6 cm, r the distance from its center to any point on the ground, dr the thickness of an elementary shell of earth concentric with it, I the total current flowing, E the potential applied, R the resistance, and ρ as above. The resistance to flow of current through the shell will be dR. Now $dR = \frac{\rho dr}{2\pi r^2}$ and $dE = IdR = \rho I dr / 2\pi r^2$. Whence $E_r = \frac{\rho I}{2\pi}\int_{r1}^{r}\frac{dr}{r^2} = \frac{\rho I}{2\pi}\left[{}^{1}/_{r_1} - {}^{1}/_{r}\right]$. Substituting for ρ and I, $E_r = \frac{3600 \times 59}{2 \times 3.1416}\left(\frac{1}{r_1} - \frac{1}{r}\right) = 33\ 800\left(1/r_1 - \frac{1}{r}\right)$. From this formula E_r has been calculated for different values of r and plotted in Fig. 27. The resistivity of the metal composing the electrode is neglected.

The two curves exhibit a marked degree of similarity. In addition, such measurements as have been made indicate that in the majority of cases measured values and calculated values will fall in close relation to each other, and for these reasons the curve for the pipe can doubtless be regarded as fairly typical of pipes driven in normal soil, at least for pipes up to 10 feet in length. At the same time, however, it should be stated that in many cases there will be wide deviations from the calculated curve, the extent of the deviations depending upon the condition of the soil in the immediate vicinity of the pipe, and also upon the firmness with which it is packed against the metal. Moreover, as the length of the pipe increases there is a tendency for the

curve of potential differences to become flatter and approach a curve represented by the expression. $E_r = \frac{\rho i}{2\pi} \log_e \frac{b}{a}$. This expression applies to a pipe or rod extending into the earth to such a depth that current flow away from it at the top is radial.

The quantity i is current per unit length of the electrode, a the radius, and b the distance from the axis to any point on the ground.

On the other hand, from the closeness with which the circles representing potential differences at 143 volts fall with respect to the curve through the dots, it is evident that the shape of the curve will be the same whatever the voltage. With the aid of this curve, therefore, and the resistance and current flow, a rough idea may be obtained in any given example of the potential differences between the pipe or earth wire leading to it and near-by points on the ground. For instance, if the resistance is 25 ohms and the current 6 amperes, the total voltage will be 150. This is nearly 0.22 of 684 volts. Therefore, upon multiplying this factor, or 0.22, into the ordinates of the curve in Fig. 27, it is seen that at a distance of 2 feet the potential difference between earth wire and ground will be about 66 volts; at 4 feet about 92 volts, and so on. As the current flow increases the potential differences will also increase in the same proportion, unless there is marked heating near the electrode. In this event the increase of temperature will cause the resistivity of the soil near the electrode at first to decrease, which in turn will cause the potential differences between the pipe and points near by also to decrease, but as heating proceeds to such a degree that drying of the soil occurs an opposite effect is produced. The resistivity increases enormously, which causes the potential differences in turn also to increase. For example, when No. 4 failed under too great a rate of dissipation of energy the difference of potential between the pipe and a point on the ground 1 foot away reached a value of 885 volts, instead of 100 or so as it would have if drying of the soil had not occurred. Consequently, in making earth connections in practice, careful consideration should be given to the possibility of failure through excessive flow of current.

At this point it may be mentioned that salting has an important effect, not only upon the capacity of a ground connection to dissipate energy, but also upon the potential gradient, especially in the vicinity of driven pipes. To demonstrate this effect an

experiment was made upon a 0.75 inch pipe driven to a depth of 5 feet in rather stony clay soil, with similar pipes driven at various distances away from it to serve as contacts in measuring potential differences. The first step taken was to impress 145 volts upon the driven pipe in series with a water pipe ground. The current was found to be 2.05 amperes, and the resistance, therefore, was 70.6 ohms, which corresponds to a soil resistivity $\rho = 2 \times 3.1416 \times 28 \times 70.6 = 12\,450$ ohms per cubic centimeter; that is, if the resistance of the water pipe ground, which was about 1 ohm, is neglected. The potential differences were measured with a voltmeter having a range of 150 volts and a resistance of 1996 ohms. The resistance to flow of current away from each driven pipe serving to make contact with the earth was known so corrections were made to the voltage readings, this correction being about 4 per cent. The results are shown plotted in Fig. 28, each potential difference being represented by a dot.

The next step was thoroughly to salt the specimen. A hole about 2 feet in radius and 1 foot deep was dug around it, 65 pounds of salt poured in, and covered with earth. At intervals of two or three days the soil was flooded with water to dissolve the salt and carry it deeper into the ground. The potential measurements were then repeated. With 145 volts impressed the current was found to be 6.6 amperes. The resistance, therefore, was 22 ohms, or about 31 per cent of its original value. This reduction is mostly due, of course, to the effect of the salt in lowering the resistivity of the soil near the pipe, but is also in small part due to the water used to dissolve the salt and to a rainstorm which increased the moisture content in the entire region. Nevertheless, any changes in the shape of the curve showing potential differences may be nearly all attributed to the salt, because a uniform change of resistivity due to rainfall would have no effect beyond decreasing the total resistance, and as the soil was quite moist to begin with, the water poured around the pipe would not produce an effect on the resistivity of the soil in any way comparable with that produced by the salt. The results are plotted in Fig. 28, the potential differences being represented by circles.

In Fig. 28 there are also plotted calculated potential differences for a hemispherical electrode in the same way as in Fig. 27. The radius of this hemisphere is taken as 28 cm (0.918 feet), or numerically equal to the combined electrostatic capacity in free space of the pipe and its image in the surface of the ground, as shown by Table 1. When buried in soil of resistivity equal to 12 450 ohms

per cubic centimeter, the resistance will therefore be the same as for the pipe, or 70.6 ohms, and with 145 volts impressed the current will be 2.05 amperes. Substituting these quantities in the formula $E_r = \frac{\rho I}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r}\right]$, results are obtained for different values of r, which correspond to the upper broken-line curve. On the other hand, the lower broken-line curve represents potential differences calculated on the assumption that the soil surrounding the hemisphere to a distance of 2.9 feet from its center is salted in the same way as described for the pipe. The quantity of salt placed around the pipe was sufficient to make nearly a 2 per cent solution of the soil water in a cylinder the length of the pipe, concentric with it, and about 2 feet in radius, if the moisture content is taken as 30 per cent. The soil was quite moist, so it is likely that this value is about right. From Fig. 26 it is seen that adding 2 per cent salt to the soil moisture decreases the resistivity by about 13 times. Assuming this to be the case for the pipe, the resistivity of the soil for 2 feet from it is roughly 1000 ohms per cubic centimeter. Beyond that it is greater, but because of the rain must be taken as less than 12 450, as indicated above. The calculation will come out about right if it is considered to be 10 170 ohms per cubic centimeter. That is, with $\rho=1000$ ohms per cubic centimeter to a distance of 2.9 feet from the center of the hemisphere, and 10 170 ohms per cubic centimeter beyond that, the total resistance to flow of current will be 22 ohms, and with 145 volts impressed the current will be 6.6 amperes. Substituting in the formula for E_r results are obtained which correspond to the lower broken-line curve of Fig. 28. The similarity between the curves representing calculated and measured values is even more marked than in Fig. 27.

The effect of the salt in changing the potential gradient near the pipe is practically that which might be expected from previous study of its effect on the resistivity of soil. In the main the change may be regarded as beneficial, although as far as danger to animals is concerned there is scarcely any improvement. For if a large animal, such as a horse, were standing near the pipe with front feet 1.5 feet from it the rear feet would be approximately 5 feet farther away. From Fig. 28 the potential difference between these two points is seen to be about 35 volts before salting, whereas afterwards it is about 70 volts. Hence, the application of salt appears to cause an increase in the danger to animals, but with regard to persons the danger is lessened, be-

cause injury is most likely to occur through touching the pipe or earth wire, and salting causes a marked reduction in the potential differences between the pipe and points within reaching distance of it. The greatest advantage, however, is that mentioned heretofore, viz, reduction of resistance, which facilitates the operation of protective devices.

With regard to plates, or other electrodes buried beneath the surface of the ground, the potential gradient is not nearly so important a matter as in the case of pipes or electrodes which are accessible. For with the former the region of greatest potential

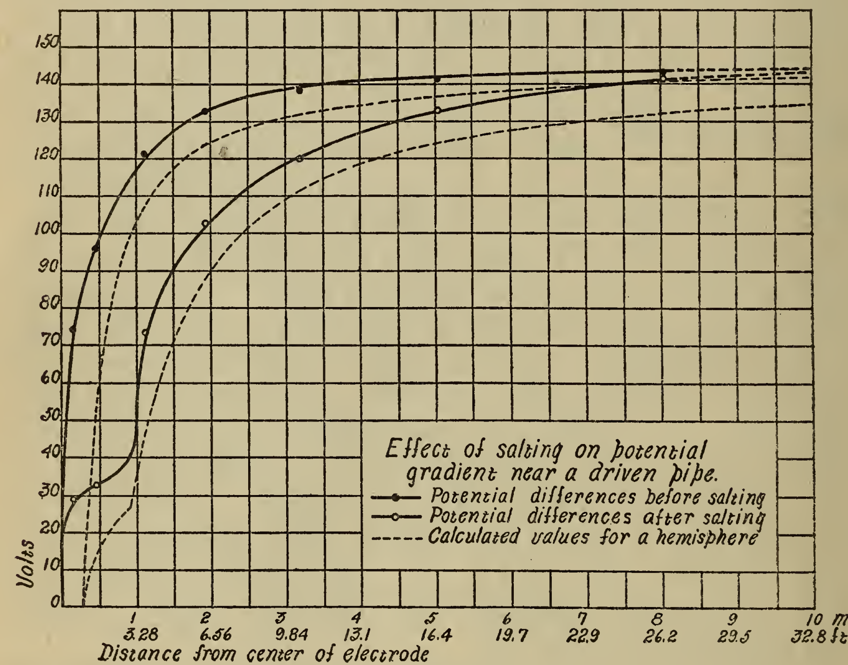

Fig. 28

gradient is underground and out of reach of persons, whereas that found at the surface is not likely to be of much moment. For instance, with a plate buried at a depth of about 6 feet, having a resistance of 2.2 ohms, and carrying a current of 100 amperes, the potential gradient immediately over the plate proved to be about 4.5 volts per foot.[36] A potential gradient of this magnitude would present very little danger to either persons or animals. Electrodes at lesser depths, of course, might show greater values, but only in extraordinary cases would they be sufficient to be of importance.

[36] Sparks, Journal I. E. E., 53, p. 401.

The greatest danger from ground connections made with electrodes buried beneath the surface arises from the high potential differences which may exist between the earth wire and points within reaching distance of it when current is flowing. In the case just mentioned this was 150 volts, the total voltage, being 220. With the earth wire well guarded, however, and every part of the ground connection mechanically strong, as described below, the likelihood of injury from it is very small.

V. MECHANICAL CONSTRUCTION OF GROUND CONNECTIONS

Substantial construction is one of the first considerations in making ground connections of any type and should never be sacrificed to expediency. For if grounding is poorly done it might in most cases as well not have been done at all; ground wires break, clamps come loose, electrodes corrode away, and even though repairs are constantly attended to, the protection afforded may be inadequate and unreliable. Moreover, the presence of a ground connection of any kind engenders a feeling of security which is false unless the materials and workmanship are of the best. Too much emphasis can hardly be laid upon the necessity for carefulness in this particular feature of electrical practice.

1. DRIVEN PIPES

In driving pipes difficulties are sometimes encountered, and as a consequence the work is not uncommonly slighted. The chief difficulties are presented by stones and crumpling of the pipe under the hammer. In some localities stones are so numerous as to prevent driving altogether, but very stony ground can be penetrated by first driving a steel bar with a tempered point. The bar can stand almost any amount of hammering, and when it is removed the pipe can be driven in the same place with comparative ease. By this means a good ground connection may in many cases be obtained where otherwise the operation might result in a waste of material. The size of the bar should be somewhat less than that of the pipe, because if the hole is made too large some time may be required for the soil to settle, and in the meantime the resistance is not unlikely to be so high as to be unsafe.

With a bar driven 10 to 12 feet in the ground considerable force is necessary to remove it, and where many ground connections

are to be made a great deal of time can be saved by making adequate preparations in advance. The force required may be estimated at from 3 to 4 tons. For applying it a 3-ton differential pulley will probably be found satisfactory, although other means may be used with good results; for instance, a lever of the proper dimensions, a lifting jack, or a chain and fulcrum with a team of horses or a motor truck. The bar may well have a heavy hook welded on near the top for attaching the chain in pulling. The pull should be as nearly vertical as practicable to avoid bending the bar or widening the hole.

In soft ground, however, or even rather hard ground where there are few stones, pipes may readily be driven to the required depth without the use of a bar. The greatest trouble which will be met with in this case, and also in stony ground, is crumpling and bending at the upper end. With ordinary galvanized iron pipe this is not easy to avoid. Nevertheless, if the hammering is not severe a coupling screwed on a threaded end as far as it will go will in some cases serve very well to prevent it, but these couplings split easily, or the pipe may break off in the thread. On the other hand, if heavy hammering is required, a more satisfactory method is to drive 4 to 6 inch lengths of lap-welded steel conduit over the end of the pipe. If the end is threaded or otherwise a little reduced in size, a 1-inch conduit can be driven over a 0.75-inch pipe or a 1.5-inch conduit over a 1.25-inch pipe. This conduit is tough and will be of great assistance in preventing battering. But where a great deal of pipe is to be driven which is all of the same size the most satisfactory method is to make a cap of mild steel similar to that shown in Fig. 29. The shank *A* is made to fit rather snugly on the inside of the pipe, and the circular slot *B* is of a width but little greater than the wall thickness. The farther *A* extends into the pipe the more effective it will be in preventing bending. Such a cap will serve for a great many pipes before wearing out.

In general it will be found that the medium sizes of pipe drive better than either the smaller or the larger sizes, as they can withstand far more hammering than the smaller sizes and at the same time do not require as much of it as the larger ones. In fact, in stony ground it is extremely difficult to drive a 2 or 2.5 inch pipe to the requisite depth even though a bar is driven in advance. For general purposes, therefore, the 1 or 1.25 inch sizes may be considered preferable. They can be driven with either square or

flattened ends, but neither seems to present a marked advantage over the other. The use of extra heavy pipe is to be recommended on account of its greater strength to resist the effects of driving and also the greater amount of metal to resist corrosion.

After a pipe is driven the crumpled part should be cut off near the surface of the ground with a hacksaw, the exposed end threaded, and a brass casting screwed on which is made with a lug to which the earth wire can be soldered, or an ordinary coupling can be used at the surface of the ground and the pipe extended upward 8 or 10 feet if beside a pole or building. The joint between wire and pipe is thus removed from the possibility of mechanical injury. Where a number of pipes are to be connected together, pipe and ordinary fittings may be used, or brass castings and copper wire. With either the connections can best be placed underground, where they will be better protected from breakage than if exposed. Wires should be laid slack for the reason that if they are disturbed they are less likely to be broken.[37] Joints, or places where the galvanizing has been impaired, should be well daubed with hot pitch or tar and wrapped with cloth, or otherwise protected from soil corrosion. The brass castings just mentioned can be purchased in the market. In place of them, however, a good joint between wire and pipe can be made by driving a wooden plug into the pipe until it is 3 to 4 inches below the top, inserting the wire and pouring the hole full of melted lead. Where salt is used it is advisable to dig a hole around the pipe to a depth of 1 foot or so, dump in the salt, and cover it with earth. With the salt buried in this way there is no chance of its being carried away by surface water, and its proper distribution through the soil is assured. To hasten distribution at first, water may be used, but this should not be overdone, as a large part of the salt may be washed away. As much dependence as practicable should be placed upon natural diffusion.

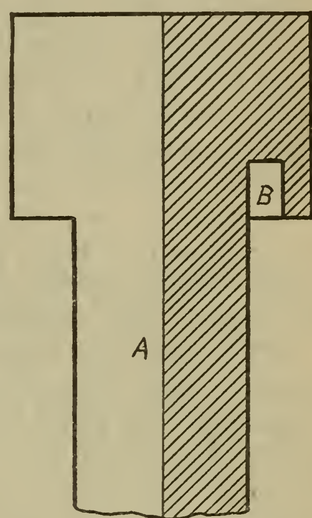

FIG. 29.—*Cap for driving pipe*

[37] See Rule 93*d*, Appendix II.

2. PLATES

In selecting materials for ground plates much depends upon the length of life required of them. If they are intended to be practically permanent, copper, of course, is about the only metal commercially available which will serve the purpose, although galvanized iron, will last for a number of years, even where salt is used, and is much less expensive. The thickness of a plate has very little to do with the resistance to flow of current away from it, and is therefore determined solely by mechanical considerations and the extent of the corrosion that is likely to take place. In general Nos. 14 to 18 gauge sheet metal will be found satisfactory in either copper or iron. With iron, however, because of its greater susceptibility to corrosion, heavier sizes may be used to slight advantage on account of the greater amount of metal, but it should be remarked that it is upon the galvanizing that the most of the life of such a plate depends. Hence, none but the best quality of galvanized sheet should be considered. Cast-iron plates do very well in some cases, being especially resistant to corrosion in ordinary soils. But, on the other hand, any of these materials may corrode very rapidly if exposed to some soils or to seepage from dumping places.

With plates the connection between electrode and earth wire must be made underground. This puts the joint out of reach of inspection and precautions are therefore necessary to make it last as long as the plate does. A procedure which has in many instances been recommended, and which is, perhaps, as good as any, is to use a heavy earth wire, or preferably a strap of metal, which can be riveted and then soldered, the strap extending a foot or so over the surface of the plate. After the soldering is done it is advisable thoroughly to clean the metal around the joint and coat it with tar or pitch to prevent corrosion. If the plate and earth wire are of different metals, this corrosion, due to galvanic action, may be considerable. If both are of copper, however, there is little danger of damage from this cause.

When plates are buried, care should be taken to make as good contact with the soil as practicable, for the effectiveness of the ground connection depends to a considerable extent upon the thoroughness with which the earth is packed against the metal. If the plate is placed on edge, no particular care in this respect is necessary; tamping on each side of it is sufficient. But if it is laid flat and the ground is stony, all of the stones should be removed

from the bottom of the hole, and, whether the ground is stony or not, the soil upon which the plate is to rest should be loosened to a depth of several inches. With this bed of loose earth, and the hole filled and rammed, good contact is likely to be obtained. Otherwise, the plate may rest on lumps and in that way make contact with the ground only in spots. It is also to be recommended that all stones be removed from the immediate vicinity of the plate whether it is placed on edge or flat, because, as previously mentioned, they are of high resistivity, and many of them nearby will affect the resistance to a marked degree. If salt is considered necessary, it can be worked into the loose soil around the plate. It can be renewed by burying it in much the same way as described above for pipes, and allowing natural diffusion to distribute it through the region below. Where coke is used, no particular care need be exercised beyond ramming it into the bottom and sides of the hole to insure good contact between coke and soil. It may be well to loosen the soil before putting in the coke, for better contact can thus be made.

3. STRIPS

The making of earth connections with strips involves nothing radically different from the process of making them with plates. The same kinds of metal may be used and for the same reasons. Joints may also be made in the same way, but since they are likely to be near the surface of the ground it may be well to protect them, not only against corrosion, but also against mechanical injury, by embedding them in concrete. Where the joints to be protected are those between strips and down conductors, or earth wires, the concrete should be flush with the surface of the ground and of sufficient volume to prevent its being easily moved, say a cylinder 8 to 10 inches in diameter and 1 foot long. It is true, of course, that the strip can be brought out of the ground at the point where it is attached to earth wires, which limits the possibility of corrosion, but at the same time this exposes the joint to mechanical injury. On the whole it seems better to keep such joints beneath the surface and protect them with concrete. In fact, this is a desirable means of protecting joints of any kind made underground which may be subject to galvanic action in the presence of moisture or be in need of mechanical reinforcement.

4. WATER PIPES

Where connection is to be made to a cast-iron pipe line with bell and spigot joints the most satisfactory method is probably that

prescribed by the National Fire Protection Association. This method consists in drilling a hole in the bell, tapping it, and screwing in a brass plug to which the earth wire is soldered. The joint thus made requires only a reasonable amount of labor and is permanent, especially if the surface of the plug and pipe in the immediate vicinity is heavily coated with pitch or something else to prevent corrosion. On the other hand, if connection is to be made to a service pipe which can be drained of water the wire can be wrapped several times around it and soldered, or a fitting can be utilized by screwing a plug into it and soldering the earth wire to the plug in the same way as described for bell and spigot joints. But if the pipe can not be drained conveniently the next best thing is a clamp to go around it, with a lug to receive the earth wire. To insure high conductance all scale and rust should be thoroughly removed before the clamp is put on. The pipe and clamp may also be treated with one of several amalgams now obtainable which are designed for the purpose of making good electrical connection between metallic surfaces which can not be soldered.

The selection of a clamp for attaching wires to service pipes requires some care in order to obtain a device that will maintain permanent contact. There are many clamps on the market, but such of them as have been examined at the Bureau of Standards appear to be of flimsy construction. The most of them consist of a copper strip not thicker than No. 20 gauge and about 0.75 inch wide, which encircles the pipe and is held by a set screw or small bolt passing through holes punched in the copper. Drawing the screw to a sufficiently firm grip puts too great a stress on the metal, and, in fact, strains it to such a degree that good contact is difficult to maintain. Moreover, in some cases lugs for the earth wire are not provided; one end of the copper strap is simply bent to the required shape. In view of these facts more substantial construction of clamps seems necessary. The metal used should be much thicker, say about No. 8 gauge, and a lug for the bolt should be riveted to each end of the strap. There should also in every case be a lug for the earth wire put in such a position that tightening the bolt results in a firm and permanent electrical contact.

The place at which it is desirable to make connection to service pipes must also be considered. In general, it may be stated that it should be so chosen that there is the least likelihood of the pipe being disconnected between the point at which the earth

wire is attached and the water main.[38] Moreover, where the water meter is placed in the basement of a building the point of attachment should be on the street side of the meter. Or, if the meter is located in a well or manhole under the sidewalk or street, a jumper, consisting of a wire as large or larger than the earth wire, should be placed around it. The necessity for these precautions arises from the fact that plumbers in making repairs may disconnect the pipe and destroy the effectiveness of the earth connection. Also, it is the practice of some water companies to remove water meters when buildings are vacated. It is desirable, however, to maintain the ground connection at all times, particularly if the circuit to which it is attached serves other customers in the vicinity, and the contingency presented by the removal of the meter can best be guarded against by shunting it with a heavy wire.

5. GROUND WIRES

The minimum allowable size of ground wires is determined principally by mechanical considerations, for they are more or less liable to mechanical injury, and must therefore be strong enough to resist any strain that is likely to be put upon them. The general practice in electrical construction is to place the minimum size at No. 6 copper, particularly for grounding circuits carrying current. This size is also specified in most codes of rules for the same purpose. The extent to which No. 6 is adhered to as a minimum size under all conditions is indicated by correspondence with electric companies.[39] In all, 418 companies were heard from. Four reported as using wires smaller than No. 6, 152 made no answer, while 262 reported as using No. 6 or larger. Hence, in view of the general use of No. 6 as a minimum size, it seems that it can be taken for granted that it is quite satisfactory, especially as there are no reports to the contrary. On the other hand, for earthing frames of machines and other noncurrent-carrying parts of electrical equipment it may in some cases be permissible to use smaller wires if they can be put where they are out of the way of possible damage. These smaller sizes, however, should be used only under certain conditions. For instance, if a small motor is connected to a low-voltage line which is already grounded for protection against high voltage, it is desirable also to ground the frame of the motor, but it is not so important a matter as it would be if the circuit from which energy is taken

[38] See rule 95a, Appendix II.

[39] This correspondence is summarized in Appendix I.

were insulated. Under such conditions breakage of the ground wire is not likely to be so serious. Consequently the ground wire used for the frame in this case, and also in all similar cases, may be smaller than No. 6, provided it is of sufficient current-carrying capacity, but it does not seem safe, even under such circumstances, to use wires smaller than No. 14.[40]

The current-carrying capacity required of a ground wire is determined by the maximum current which the ground connection will be obliged to pass in the event of an accident to insulation, which in turn is determined by the rating of the nearest cut-out which will operate to break the circuit. The ground wire should under no circumstances be too small to carry this rated current safely. For lines, therefore, the ground wire will in most cases be of the same size as the line wire to which it is attached, but not in every case, because the line may be overhead and the ground wire inclosed for a considerable distance in wooden molding, and under such circumstances the ground wire would have to be larger than the line wire in order to provide a safe current rating. A contingency of this kind, of course, may arise infrequently, or not at all, but is cited here to emphasize the fact that the size of the ground wire should be determined by the rating of the nearest cut-out if it is greater than the safe current for the minimum size wire as set forth above. On the other hand, if it is smaller it has no effect on the size of the ground wire. It may be added that the foregoing remarks concerning ground wires for lines apply with equal force to ground wires for the noncurrent-carrying parts of electrical equipment.

The path of the ground wire should be as far as possible out of reach of persons, for it is to be considered dangerous, and as much care must be taken to make it inaccessible as would ordinarily be taken with a low-voltage line wire.[41] Where practicable this can best be effected by bringing it to ground from a point directly above the place where the electrode is buried. The portion accessible from the ground can then be guarded, both against mechanical injury and contact by persons. For this purpose it is preferable in every case to use guards of insulating material. Mechanical injury can, of course, be prevented by inclosing the wire in iron pipe or conduit, but the presence of the iron is objectionable because it acts as a choke coil and prevents free passage of alternating or oscillating currents, particularly those due to lightning, unless the wire is connected to the conduit at both

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[40] See rule 93*b*, Appendix I.

[41] See Rule 93*c*, Appendix II.

ends. The latter does away with the choking effect, but introduces a second difficulty in that the conduit takes the potential of the ground wire in the event of current flow, and therefore may be dangerous. Hence, it seems that guards of insulating material are in every way preferable. Wooden molding serves the purpose very well and probably is as fully suited to it as anything. It is not intended, however, to convey the idea that there are no instances wherein iron conduit may not be used. On the contrary, such instances frequently arise, particularly in earthing frames of direct-current machines to water pipes, and in other cases. In fact, it may be stated that if the resistance of the earth connection is very low, and there is slight chance of the passage of alternating or oscillating currents, iron pipe or conduit may safely be used for mechanical protection, although it should be remembered that the best degree of electrical protection for persons is not at the same time secured.

VI. INSPECTION AND TESTING

1. INSPECTION

To obtain continuous and reliable service from ground connections good mechanical construction must be supplemented by adequate inspection.[42] The protection which the ground connection affords life and property may be destroyed by mechanical injury or corrosion, and it is therefore absolutely essential to safety that any defects found be remedied at the earliest practicable moment. That inspection has in many cases in the past been inadequate is shown by the correspondence with electric companies previously mentioned. Of the 418 companies from which replies were received, 132 reported as inspecting at intervals ranging from six months or less to five years, 59 reported no systematic inspection, 12 no inspection whatever, while 215 made no answer to the question regarding inspection. Of the entire number, 260 stated that they grounded low-voltage alternating-current circuits, and since only 191 reported inspection, it appears that something like 69 do no inspecting at all. Moreover, many of the 191 inspect so irregularly that the results are of little value. Of the 132 making regular inspection, however, 81 stated that they inspected at intervals of one year. This is a more or less satisfactory interval, and if adhered to will lead to fair results,

[42] See Rule 96*b*, Appendix II.

for the reason that deterioration by corrosion is not likely to produce marked effects in a single year.

Nevertheless, on account of the possibility of mechanical injury a shorter interval than one year is desirable. Under favorable circumstances inspection can be accomplished at intervals of much less than a year in such a way that no appreciable increase of expense is incurred. For example, meter readers may be instructed to look for broken earth wires when making their rounds, if the wires are conveniently located; or consumers may be impressed with the importance and necessity of keeping the ground connection in good condition and be requested to report faults to the electric company. Other expedients may suggest themselves in individual cases. In no case, however, should inspection at intervals not exceeding a year be omitted on the score of expense or for any other reason, for it is unsafe to leave a ground connection without attention longer than this.

2. TESTING

As stated before, it is always desirable, and in many cases very necessary, to learn as much as practicable of the electrical characteristics of a ground connection before it is put in service. Chief among these characteristics may be named resistance, capacity to dissipate energy, and possible potential gradient in the vicinity. In general, the first is the most important. The second may be important, but only in special cases. For if a ground connection complies with the safety requirements in regard to resistance and permanence it is not likely to fall short in regard to capacity to dissipate energy. Moreover, the first is easy to test for, whereas tests for the second not only take considerable time, but may also consume a large amount of energy. Tests for the potential gradient on the other hand are not particularly tedious nor expensive, but in the majority of cases the results will not justify the outlay if, as just stated, the safety requirements in regard to resistance are complied with. Hence, in preparing a ground connection for service, consideration should be given to whether it is likely to carry a heavy current. If it is, and circumstances are such that a sufficiently low resistance is difficult to obtain, it may be well to test for the capacity to dissipate energy, and also, perhaps, for the possible potential gradient if there is any possibility of injury to persons or animals. These tests, however, scarcely need to be applied to ground connections other than those for electrical circuits, and then only to those for the largest and most

important circuits. On the other hand, for ground connections to noncurrent-carrying parts of electrical lines or equipment, and to circuits from which the total possible flow of current to earth does not exceed 40 or 50 amperes, a simple measurement of resistance may in all cases be considered sufficient.[43] But even this test is unnecessary in the case of connections to water pipes if there is assurance that the pipe is continuous electrically for a hundred feet or more from the point where the earth wire is attached. Where there are insulating joints, however, a measurement of resistance is advisable.

As just stated, a measurement of resistance, and in some cases a measurement of capacity to dissipate energy, and possible potential gradient, should be made upon a ground connection when it is installed. If the soil conditions are normal; that is, not extremely wet or dry or cold, the results will give a fair indication of its future behavior. Subsequent tests may be confined entirely to resistance measurements, the period elapsing between tests depending largely upon the character of the ground connection. For the fault most likely to be disclosed by resistance measurements is that of corrosion beneath the surface of the ground. And in the case of pipes this can readily be kept account of by regular inspection, but with plates, corrosion, either of the ground wire or the plate itself, is most likely to be disclosed only by tests. Hence, resistance measurements of plates should be made oftener than of pipes. Moreover, where salt is used it is desirable to know when its effects are wearing away, and this can be ascertained most easily by resistance measurements. Tests, therefore, should be made at shorter intervals than where salt is not used. As a working basis it will probably be found that for driven pipes resistance measurements once in four years will be sufficient, for plates two years, and for salted ground connections, especially those for important circuits, one year. Such resistance measurements, combined with inspection at intervals of a year or less, will in all probability scarcely ever fail to show when a ground connection needs repairs, and will enable keeping it at all times in good condition.

The indications of resistance measurements are especially valuable, for the experiments previously described show that progressive changes in the resistance of ground connections are not likely to occur except by corrosion which may sever the ground

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[43] See rule 96*b*, Appendix II.

wire or destroy the electrode. When therefore an electrode is shown by inspection to be seriously corroded, or by test to have an increase in resistance to flow of current away from it that can not be accounted for by freezing, drying of the soil, or washing away of salt, it should be promptly repaired or renewed. Discussion of methods of measuring resistance follow:

(*a*) AMMETER-VOLTMETER METHOD USING THREE CURRENT TERMINALS.—The ammeter-voltmeter method using three current terminals is the most reliable of any for making resistance measurements, especially if alternating current is available. Connections for making measurements in this way are shown in Fig. 30. Here

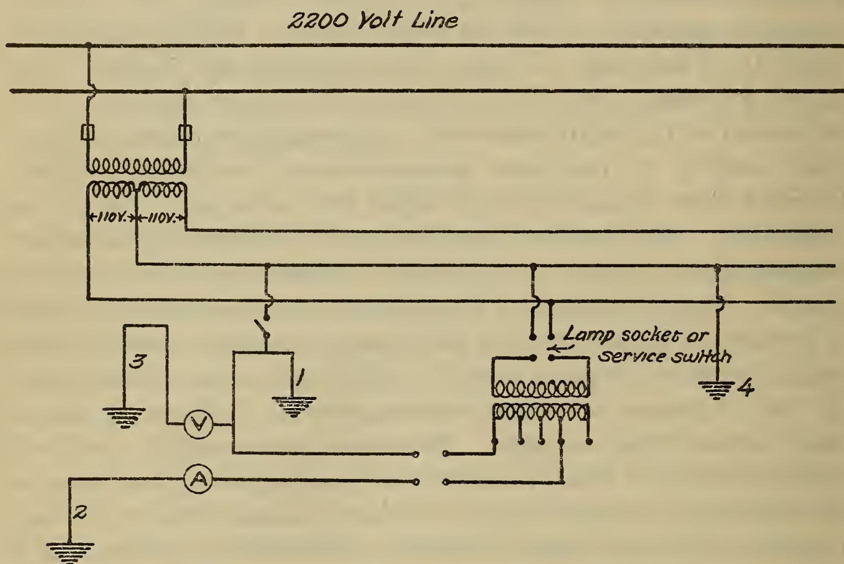

FIG. 30.—*Ammeter-voltmeter method using 3 current terminals*

a transformer having a 1 : 1, or any other suitable ratio, is connected to a low-voltage circuit through a lamp socket or a service switch. From the secondary of this transformer current is passed through each pair of ground connections; that is, 1–2, 2–3, 1–3, in series, the current and voltage in each case being read by means of the ammeter and voltmeter. From these readings the resistance between each pair of electrodes can be calculated. Let these resistances be designated by r_{1-2}, r_{1-3}, r_{2-3}, and the resistances of the individual specimens by R_1, R_2, R_3. From what has already been said on the subject of resistance of ground connections it is apparent that if 1, 2, and 3 are at some distance from each other the equations, $R_1+R_2=r_{1,\ 2}$, $R_2+R_3=r_{2,\ 3}$, and $R_1+R_3=r_{1,\ 3}$ are a fair approximation to the actual relationships existing

between these various quantities. Solving the foregoing equations it follows that $R_1 = \frac{r_{1,2} - r_{2,3} + r_{1,3}}{2}$, $R_2 = \frac{r_{1,2} + r_{2,3} - r_{1,3}}{2}$, and $R_3 = \frac{r_{2,3} - r_{1,2} + r_{1,3}}{2}$. Therefore, by measuring the resistance of each pair of electrodes in series, and substituting in these equations, results may be obtained which show very closely the actual resistance to flow of current away from each electrode. It is to be remembered, however, as mentioned above, that in every case the electrodes must be at some distance from each other, otherwise absurdities may arise in the calculations such as zero or even negative resistances.

To keep the required number of instruments at a minimum a transformer may be used, the secondary of which is wound for several voltages, such as 30, 60, 120, and 240. A single ammeter and usually but two voltmeters are then all that is necessary for measurements under ordinary conditions. Satisfactory results will be obtained in nearly all cases with an ammeter having a range of 2–10 amperes and one voltmeter reading say 80–300 volts and another 20–75 volts. To make such an outfit as portable as practicable the transformer should be small; its rating need not be greater than 0.5 kw. This size permits of connection to house lighting or power circuits and will give sufficiently large currents for accurate measurement upon any ground connection which is fit as far as resistance is concerned for grounding electrical circuits or equipment.

In Fig. 30 ground No. 1 is indicated as one of the ground connections of the low-voltage circuit. Before making the measurement the ground wire should be disconnected unless it is desired to measure the resistance of grounds 1 and 4 in parallel. Grounds Nos. 2 and 3 are of the nature of auxiliaries. These may be any piece of metal buried in the earth, such as a guy wire or a steel pole. The only conditions imposed upon these auxiliary grounds are that they be of sufficiently low resistance to give good current readings and sufficiently far apart, and from the ground connection being measured, not to interfere with the results. The greater this separation is the better, but for good results it should be at least 15 feet, although 6 feet need not be considered too small if circumstances are such that a saving of labor will result from using existing auxiliary grounds rather than making others more suitably located. At 15 feet, however, the mutual influence of the electric fields about two neighboring electrodes can be neglected as far as practical purposes are concerned.

The chief advantage of the method described above lies in the dependability of the results obtained. For, in the first place, a measuring circuit is provided which is cut off by insulation from all disturbing influences due to accidental or permanent grounds on the circuit from which energy is taken. Whereas, if the step-down transformer were not interposed between the low-voltage and the measuring circuits, and current were taken directly, a ground on the former would tend to give rise to stray currents through the ammeter that would cause errors to appear in the results. In the second place, on account of the comparatively high voltages and currents used, nothing in the way of stray currents of any kind in the earth is likely to disturb the measurements to an appreciable extent.

On the other hand, disadvantages are presented by this method in that even the lightest practicable outfit of transformers and instruments weighs so much that it is more or less inconvenient to transport; lamp sockets or service switches to which attachment may be made are not always within reach; considerable calculation is required before final results are obtained; and, if measurement is to be made upon an isolated ground connection, it may be necessary to make two auxiliary grounds. The last two disadvantages are mitigated somewhat by a modification of this method into what may be called the ammeter-voltmeter method using two current terminals.

(*b*) Ammeter-Voltmeter Method Using Two Current Terminals.—The connections for this method are shown in Fig. 31. Here current is passed through two ground connections (1 and 2) in series, and the voltage measured between the one the resistance of which is to be found (1) and a third, or potential terminal (3). The resistance is then calculated simply by substituting in the equation $R=E/I$. Under favorable conditions good results may be obtained in this way. There is a source of error, however, which must be guarded against, and that is, if the resistance of the ground connection used as the potential terminal (No. 3) is sufficient to be comparable with that of the voltmeter a considerable discrepancy will be introduced into the calculated values, because the voltage reading will be proportionately less than the actual voltage; and, unless a correction is made, the resistance being measured will also appear to be less than it really is. Reasonable assurance must be had, therefore, that the resistance of the ground connection in series with the voltmeter is low enough

to avoid serious error. In the absence of such assurance, the resistance may be measured very simply and the corresponding correction made. There may, of course, be some question as to what constitutes a serious error, but it seems that in work such as this, where approximate results are all that are required, an error need not be considered serious unless it exceeds 10 per cent.

To determine whether the resistance of the third or potential terminal mentioned above can be neglected, use may be made of a voltmeter having two scales, on both of which the voltage can be read with a reasonable degree of accuracy. Then, with current

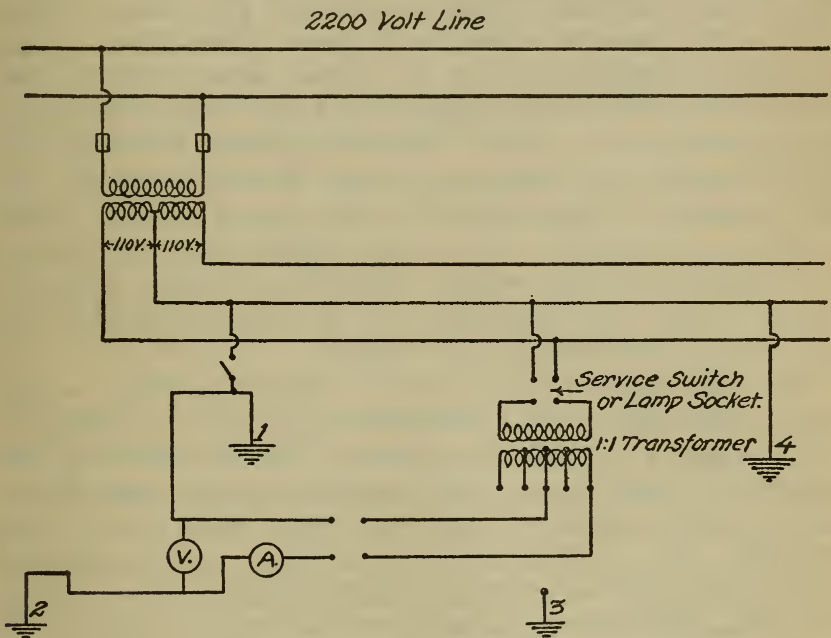

FIG. 31.—*Ammeter-voltmeter method using 2 current terminals*

flowing between the current terminals, take two readings between the potential terminal and either of the others, one on each scale of the voltmeter. If the readings are approximately the same numerically the resistance of the potential terminal can be neglected. On the other hand, if the reading on the low scale is considerably less than that on the high scale, the resistance of the potential terminal is high enough to introduce a considerable error.

The same results can be obtained by the use of a single scale voltmeter and a noninductive resistance equal in value to the resistance of the voltmeter. Take one reading with the volt-

meter alone; then place the resistance in series with it and take another. If the first reading is approximately double the second the resistance of the potential terminal may be neglected, while if the first is considerably less than double the second, a correction must be made.

This may be done as follows: Measure the total voltage and also take voltage readings between the potential terminal and each of the current terminals; then the total voltage is shared by the current terminals in proportion to the readings last mentioned. For example, if the current terminals are numbered 1 and 2, as in Fig. 31, and the total voltage is 110, while the voltage reading between the potential terminal and current terminal No. 1 is 40, and current terminal No. 2 is 30, current terminal No. 1 takes four-sevenths of the total voltage or 62.8 volts, while No. 2 takes three-sevenths or 47.2 volts. From the values so found and the current reading the resistance of either ground connection can be calculated by substituting in the equation $R=E/I$. Good results are obtainable in this way, and considerable labor is saved as compared with the method using three current terminals, because in this case the resistance of the potential terminal may be as much as half that of the voltmeter.

For very rough work the potential terminal may even be dispensed with entirely, and measurements made by passing current through two ground connections in series, measuring the total voltage and current, and assuming that the resistance of each ground connection is half the total. Here, however, the electrodes must be of the same size and shape, and be embedded in the same kind of soil to obtain results which are at all dependable.

(c) Ammeter-Voltmeter Method Using Direct Current.—It has previously been stated that alternating current is preferable for making measurements upon ground connections. There are places, however, where only direct current is available, and with it fair results may be obtained, but it is necessary to avoid sources of error which are negligible or do not exist where alternating current is taken from a special transformer. In the first place, the counter electromotive force of polarization is a considerable quantity with direct current, and to counteract it the applied voltage must be made large enough to make its effects of no consequence in comparison. For this 100 volts is sufficient, because the counterelectromotive force of polarization is not likely to be more than two or three volts, and hence, with 100 volts applied,

will not introduce an error of more than a few per cent. This means, of course, that 100 volts, or at least a large part of it, is actually to be applied to the ground connection under test, so when measurements are being made with direct current account must be taken of the fact that the total impressed voltage is shared by two ground connections in series, and if the resistance of the one under test is low, while that of the other is high, the division of voltage may be such that the effects of polarization introduces a considerable error. It is necessary, therefore, to see that the voltage is properly shared, which can be done only by making or choosing auxiliary ground connections of resistance equal to, or preferably less than, that of the one being tested. The best conditions as to division of voltage are obtained where a water pipe or a street-car rail is used for an auxiliary ground as is indicated below, since the resistance of the auxiliary here is very low. Under these conditions results practically as good as those from alternating current are obtainable, although direct current is not so convenient to work with.

In the second place, with direct current, care must be taken to ascertain whether there are ground connections on the circuit from which energy is being drawn other than those being investigated. If there are none the measurements may be allowed to go forward in the manner described above, using one or two auxiliary ground connections as the circumstances require, but if ground connections other than those being investigated do exist, and it is impracticable to disconnect them, this method must be discarded because of the errors introduced by cross currents. However, if the ground connections already existing are of sufficiently low resistance to serve as one of the auxiliaries, the test may be made by connecting the ground wire to one side or the other of the circuit, and measuring the current flow to ground, together with the voltage between the ground under test and an auxiliary ground connection near at hand, as shown in Fig. 32. The resistance is then computed from the equation $R=E/I$. The auxiliary ground in this case—that is, the potential terminal corresponding to ground No. 3 in Fig. 31—needs only to be of such a resistance as to be low in comparison with that of the voltmeter. The resistance of direct-current voltmeters being high, such an auxiliary ground is very easily constructed.

(*d*) Kohlrausch-Bridge Method.—The apparatus and connections for this method are shown diagrammatically in Fig. 33.

The apparatus consists of a single dry cell in series with a buzzer and the primary coil of a small transformer. With the switch closed and the buzzer in operation, a pulsating current traverses the primary coil of the transformer, which in turn gives rise to an alternating current in the secondary. The secondary is connected to the current terminals of a wheatstone bridge, a telephone receiver being used in place of a galvanometer for the purpose of detecting when the bridge is in balance. The bridge should preferably be one of the easily portable ones commonly used for field work, such as a Leeds and Northrup type "S" testing set. The sensitiveness of the telephone receiver should

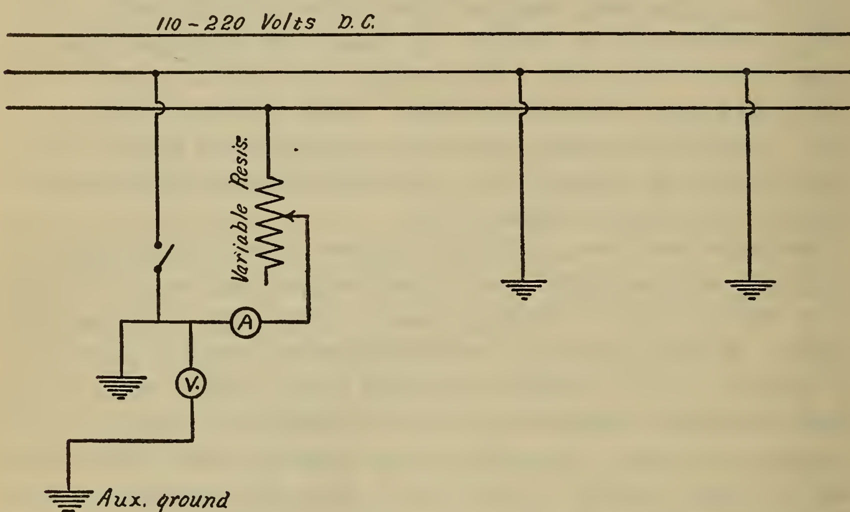

FIG. 32.—*Ammeter voltmeter method using direct current*

be rather low, because it is then less sensitive to the disturbing effects of stray current. The most suitable types of buzzer are those used in radio telegraph work, which can be made to give interruptions at a rate of several hundred per second. As to the transformer, a ratio of 1 : 10 does very well, although any other rates ranging, say, from 1 : 5 to 1 : 20, would serve. Its size is unimportant, except as far as portability is concerned. For this the lighter it is the better. There is no need of it weighing more than 2.5 pounds.

The method of procedure in making measurements is much the same as for the ammeter-voltmeter method; that is, with three ground connections at some distance from each other the resistance of each pair in series is measured and results substituted in

the equations given above. Or, if there are but two neighboring ground connections available, their resistances may be obtained by means of proportional resistances in much the same manner as in the ammeter-voltmeter method the resistances were obtained by means of proportional voltages. This method is described in detail in the next section. Finally, if there is a water pipe or a bonded rail near by, as in Fig. 33, either of these may be used as an auxiliary ground and its resistance neglected, thereby obtaining by a direct reading the resistance of the ground under test.

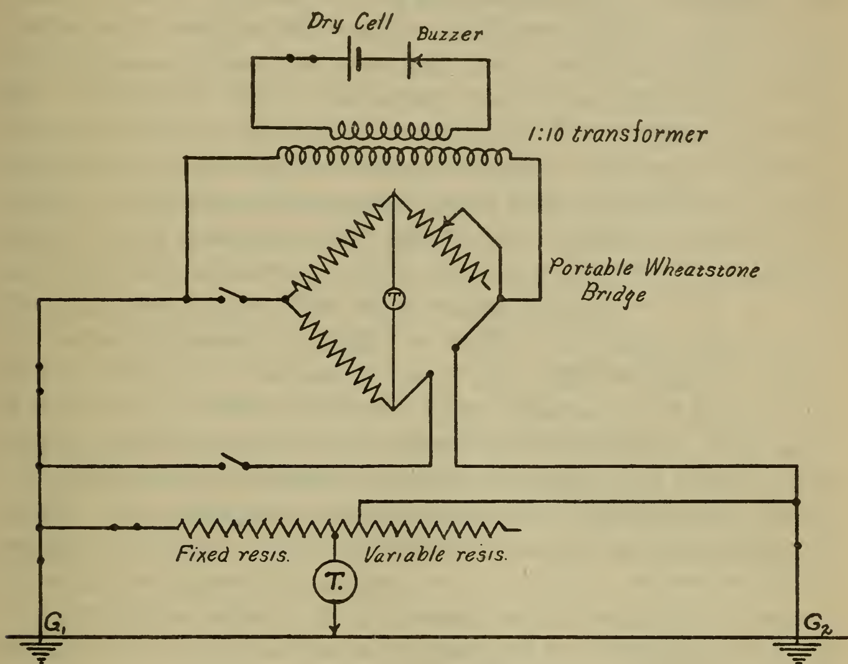

FIG. 33.—*Kohlrausch Bridge method*

The advantages of the bridge method of measuring the resistance of ground connections are as follows: In the first place, the results obtained are sufficiently accurate for practical purposes. Comparative measurements made at the Bureau of Standards show that this method and the ammeter-voltmeter method check within 2 or 3 per cent in nearly all cases, and in but few cases do errors arise which approach 10 per cent in value. In the second place, the source of energy constitutes a part of the apparatus itself, so it is not necessary to depend for measuring current upon the proximity of low-voltage circuits of any kind. In the third place, the outfit is easily portable and very rugged; and, in the

fourth place, a field experience extending over several months has disclosed but very few cases wherein for any cause the resistance of single ground connections that were disconnected from electrical circuits could not be measured. Lastly, direct readings are obtained, which do away with the need for computation.

The disadvantages of the method are not serious, but deserve some consideration here: First, the range of resistances which can be measured is limited, although it is greater than can be covered by the set of alternating-current ammeters and voltmeters heretofore described. The bridge gives good results from about 2 ohms to 200 ohms, and fair results from 200 ohms to about 3000 ohms. Below 2 ohms and above 3000 ohms it is not usually practicable to obtain measurements that are more than simply indicative of the order of magnitude of the resistance. It is very unusual, however, to encounter ground connections made with ordinary electrodes having a resistance of less than 2 ohms or more than 1000 ohms, so the inconvenience of the limits just mentioned is not great. Second, stray alternating, or even direct currents in the earth, on pipes or rails, or on the ground wire itself, may cause so much noise in the telephone receiver as entirely to obscure the sound of the bridge current, the sound produced by direct current arising from commutation, but it should be remarked here that if the ground connection being tested is disconnected from all electrical circuits the chances that stray currents will be sufficient to preclude the possibility of obtaining good results are small. Third, where an electrical circuit is grounded at several points it is practically impossible, except in rare instances, to measure the total resistance of all the ground connections in parallel with current on the circuit on account of the leakage to earth over the ground wires producing noises in the telephone receiver. Finally, if a ground connection is attached to an electrical circuit of considerable extent, or if a wire several hundred feet in length is necessary to reach the auxiliary ground, capacity and inductance effects may be such as to make it very difficult to detect the point of balance on the bridge.

The apparent reason for the failure of the bridge to operate satisfactorily outside of the limits named above is that with the arms adjusted to measure these high or low resistances the leading or lagging component of the current due to capacity or inductance in the leads produces much louder sounds in the telephone receiver than the component in phase with the impressed electro-

motive force, especially when the bridge is anywhere near a balance. The same effect is produced, with any adjustment of the arms of the bridge, if the ground being measured is connected to a circuit which is extensive enough to have an appreciable capacity between wires and earth. The result is that practically uniform sound is produced in the telephone receiver with successive settings of the dials, instead of a gradual decrease of sound as the point of balance is approached. There seems to be no feasible remedy for these effects. They could, of course, be eliminated, or at least greatly reduced, but the necessary apparatus would be too cumbersome, and the labor of making the adjustments too great, to be of any considerable assistance in the field, particularly as a real necessity for their elimination arises only infrequently. The effects of stray current may be overcome to a certain extent by making use of a telephone receiver of low sensitivity, and still further by means of a buzzer having a note much different from that of the stray currents. Leakage from circuits to ground need cause concern only where it is out of the question to cut the ground wire and splice it after the measurement is made.

It appears, therefore, that in practice the bridge method of measurement can be depended upon for reliable results in nearly all cases that are likely to arise. As stated above, it is hardly ever possible to obtain good results where the total resistance to ground of a live multiple-grounded circuit is desired, but this can be overcome by taking the grounds separately and calculating their combined resistance by means of the formula for the resistance of conductors in parallel.

(*e*) Modification of Kohlrausch-Bridge Method.—Where water pipes or rails are not available, and it is necessary to use auxiliary grounds, the resistance of which can not be neglected, application may be made of a modification of the method just described, which involves fewer measurements and less computation than the regular method, and also requires only one auxiliary ground instead of two. The procedure here is as follows: First, measure the resistance of the two ground connections in series, using the regular Kohlrausch bridge. Then connect in series between the two electrodes a fixed resistance and a variable resistance of several hundred ohms each, as shown in Fig. 34. From the point where these resistances are joined together connect a telephone receiver to ground by means of a short iron rod which can be thrust into the soil. Pass alternating or oscillating

current from the bridge set through the ground connections in series and adjust the variable resistance until minimum sound is produced in the telephone receiver. The total resistance to flow of current from one electrode to the other is shared by the electrodes in proportion to the fixed and variable resistances when adjustment is obtained. Thus if the total resistance were 30 ohms, and the resistances connected between the electrodes showed for minimum sound in the receiver 300 ohms and 200 ohms, respectively, one of the electrodes would have a resistance of three-fifths of the total, or 18 ohms, while the other would have a resistance of two-fifths of the total, or 12 ohms.

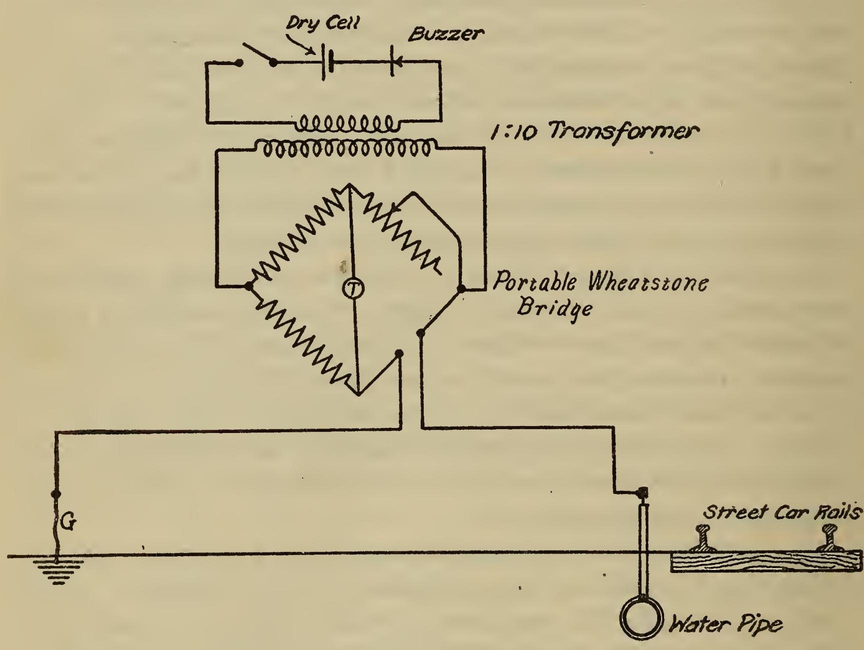

Fig. 34.—*Modified Kohlrausch bridge method*

The iron rod should be put down midway between the electrodes, or, preferably, at a considerable distance away from either of them at one side. Then, if there is a great difference in the resistances an error is not so likely to arise from being to one side or the other of the line of zero potential. The resistances for making the last measurement are readily furnished by the testing set mentioned above, that is, one of the fixed arms and the variable arm can be connected to the electrodes, the telephone receiver being put between the point where they are joined together and the ground.

The same troubles will be experienced in using this modified method as in the regular method, that is, disturbances will arise from stray currents, and difficulty will be encountered in obtaining a balance because of inductive effects due to long lead wires. Nevertheless, it is possible to obtain results in nearly all cases which are correct to well within 10 per cent. The method has been tried at the Bureau of Standards and found to be more or less satisfactory. It may be well to note here in passing that while more inconvenient than the bridge method, the ammeter-voltmeter method gives more consistent and reliable results than any other, and for that reason is preferable to any other for laboratory work, but for field work, where a certain amount of accuracy may be sacrificed to speed and convenience, the bridge method may be considered equal with, if not preferable to, the more laborious ammeter-voltmeter method.

(*f*) Testing by Lamp Banks, Fuses, and Magnetos.—At present many electric companies confine their testing operations to one or the other of the following methods: First, testing with lamp bank. This consists simply in connecting a lamp bank between one wire of the grounded circuit and the ground connection. Then, with the opposite side of the circuit grounded to a water pipe, a street-car rail, or other auxiliary ground connection that is supposed to be of fairly low resistance, current will flow through the lamp bank, and if this flow is sufficient to cause the lamps to light the resistance of the ground connection is considered low enough to give satisfactory service. Second, a two or three ampere fuse is sometimes used in place of the lamp bank. If the fuse is blown the conductance of the ground connection is taken as being suitable. Third, tests are sometimes made by means of a magneto. All that is considered necessary is that the resistance of the ground connection shall be such as to appear to short circuit the magneto when placed across the armature terminals in series with an auxiliary ground connection of some kind.

There are objections to all of these methods, for it is obvious that none of them gives even approximate information as to the resistance of the ground connection being tested, nor do they give any distinction as to different resistances for different purposes, since the same criterion is applied indiscriminately to earth connections for circuits of all capacities. It is true, of course, that blowing fuses and lighting lamp banks indicate that the resistance is within a certain maximum, but beyond this no informa-

tion is given. As for the test with a magneto it may be said that it gives no information at all, for if a magneto has an internal resistance of 600 ohms it would appear to be practically as thoroughly short circuited by 50 ohms as by 5 ohms, if the only means used for the detection of a completed circuit were the force required to keep up the speed, or the ringing of a bell, both of which are commonly resorted to where magnetos are much used in searching for accidental grounds.

It seems, therefore, that with the exception of rare cases these methods of testing ground connections should be discarded in favor of some more reliable method. The lamp-bank or fuse method may serve very well in testing for a broken ground wire, or for some similar purpose, but is of no use where it is necessary to know approximately the actual resistance of a ground connection. The magneto method should be abandoned altogether. Mere inspection is likely to tell as much of the resistance of a ground connection as this method of investigation. The chief disadvantage of the ammeter-voltmeter method or the bridge method, as compared with the less desirable methods described above, is, of course, the cost of the original outfit, but the increase in the value of the information obtained is well worth the outlay.

(*g*) Single Voltmeter Method.—Mention should be made here of another method which, as some times applied, is also very unreliable. In this a voltmeter is first connected across the line as shown at *A* in Fig. 35. The middle wire of the secondary circuit is then grounded at G_2 to the most convenient piece of buried metal within reach, and the voltmeter transferred to position *B*. The grounds G_1 and G_2 are then in series with the voltmeter, and the voltmeter reading at *B* is less than at *A* in proportion to the increase in resistance in the voltmeter circuit. If the reading at *B* is approximately the same as at *A*, the resistance of ground G_1 is considered low enough, whereas if the reading at *B* is a few per cent less than at *A* the resistance of ground G_1 is considered too high. It is obvious that the degree of accuracy obtained depends largely upon the resistance of the voltmeter. If this resistance is 3000 ohms, a change of 1 per cent in the reading between positions *A* and *B* would mean that the sum of the resistances of G_1 and G_2 in series was 30.30 ohms. A change of 2 per cent would mean 61.2 ohms and so on. To read accurately such small changes in deflection is, however, very difficult, and if there are fluctuations of voltage on the line it may appear that G_1 and G_2 have negative resistances, as would be the case if a

voltage rise should occur while changing from A to B. This could be overcome by using two voltmeters and taking simultaneous readings, but even in this way to tell the resistance of a ground connection within 50 or 100 per cent is out of the question unless a voltmeter of very low resistance is used.

(*h*) CAPACITY TO DISSIPATE ENERGY.—To test for the capacity of a ground connection to dissipate energy requires an auxiliary ground connection which can carry a greater current without a material increase of resistance than the one being investigated. Otherwise, the auxiliary ground will fail, and all the knowledge that is gained will be comprised in the fact that the ground con-

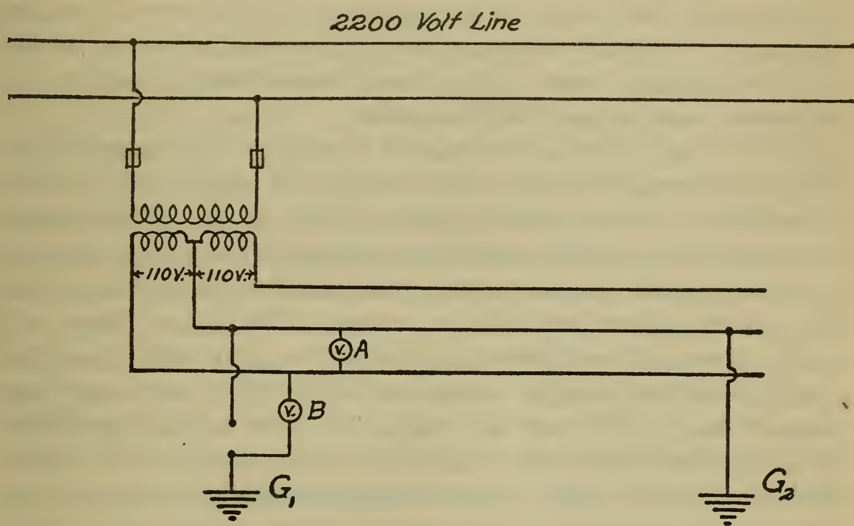

FIG. 35.—*Single voltameter method*

nection under test can dissipate energy at a higher rate than the other. In few cases, therefore, will it be found practicable to carry out satisfactory experiments unless the trouble and expense is incurred of making very elaborate auxiliaries. This difficulty does not arise, of course, where the ground connection to be investigated consists of several electrodes in parallel, for it may in such cases be possible to take each electrode separately, using the remaining ones as auxiliaries, and assuming that the total capacity to dissipate energy is equal to the sum of the individual capacities. Nor does it arise where there are water pipes within reach, although ordinarily under such circumstances the water pipes themselves should be used for grounding, which does away with the necessity for tests, but to investigate a single isolated

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electrode requires the installation of a second ground connection of even greater conductance than the first. Local conditions will determine to a large extent the exact manner in which a test may best be conducted.

If power is supplied from transformers the capacity should, for the best work, be sufficient to run the rate of consumption of energy up to about 100 kw at 1100 volts. A larger power rating than this will hardly be required in any case, and in many, in fact, a smaller rating will do very well. Means should be provided for varying the voltage through rather a wide range, such as a water rheostat in the primary circuit. The current should be measured and also the voltage between the ground connection under test and a reference electrode embedded in the ground at some distance away. For these measurements current and potential transformers will be needed.

The first step in the experiment is to estimate the current which the ground connection will safely carry, and regulate the voltage accordingly. At the end of half an hour or so, if the current flow has not changed, it should be increased. Successive increases of current should be made at intervals until steam begins to come off. On the other hand, if the current at first is too large, and steam comes off very shortly, it must be decreased. In either case the current must be reduced until steaming ceases and then allowed to flow for several hours. If there is no appreciable increase of resistance the value of the current flow at the end of that time may be taken as the maximum which the ground connection will carry without excessive drying of the soil. But if an increase of resistance does occur, the current should be still further reduced until the resistance remains constant or nearly so. From the current and voltage the rate of dissipation of energy can be calculated, the voltage, as stated above, being that measured between the electrode under test and a reference electrode embedded in the ground at a distance of 15 feet or more.

(*i*) Potential Gradient.—Where it is desired to measure the potential gradient it is only necessary to pass current through the ground connection by means of an auxiliary ground and measure potential differences, either between points on the ground or between the electrode and points on the ground, depending upon the character of the electrode and the data required. For measuring potential differences a high-resistance voltmeter is preferable. Contact with the earth can be made by means of a small plate which can be pressed into wet soil, or a bar or pipe which can be

driven to a depth of 1 foot or so. The most important matter to be observed is one already mentioned, viz, that the resistance of the earth contact in series with the voltmeter be not so large as seriously to interfere with the readings. Furthermore, the voltage actually impressed upon the electrode under test must be great enough to give good readings on the voltmeter. This may require an auxiliary ground of rather low resistance in order that the voltage shall be properly shared, but it is essential to good results. Finally, if the current is sufficient to cause heating it should be left on only while readings are being taken, and discontinued while the earth contact is being moved from place to place.

(*j*) Low Voltage v. High Voltage in Testing.—In testing ground connections it sometimes appears that their resistance is an erratic thing which it is impossible definitely to ascertain. The experience of a number of persons has led them to believe that if a low voltage is impressed one value of resistance will be obtained, whereas if a high voltage is impressed the resistance will turn out to be something altogether different. From this it has been concluded that some kind of contact resistance exists between the metal of the electrode and the surrounding soil which requires a high voltage to overcome it before current can flow freely from the metal into the earth. That such a conclusion should be reached is not strange, but that the premises upon which it is based are not correct is shown by the discussion in regard to contact resistance given in the first part of Section II on the resistance of ground connections, and also by the measurements recorded in Table 12.

TABLE 12.—Comparative Measurements of Resistance

Ground No.	Ammeter-voltmeter method						Bridge method
	Voltage	Resistance	Voltage	Resistance	Voltage	Resistance	Resistance
		Ohms		Ohms		Ohms	Ohms
1–5	118	29.1	232	30.7	1130	28.4	....
2–5	118	28.0	232	27.6	1120	27.0	....
3–5	118	32.1	233	31.9	1130	31.2	....
4–1	116	20.0	234	18.7	1080	18.4	....
5–4	118	24.3	231	23.8	1095	23.8	....
6	66.5	15.3	....	....	....	....	17.0
7	75.0	33.3	....	....	....	....	32.0
8	77.0	33.4	....	....	....	....	32.5
9	115.0	377.0	....	....	....	....	380.0
10	85.0	42.5	....	....	....	....	41.0

These measurements were made on driven pipes, all of which were 10 feet in length with the exception of No. 9, which was 1 foot in length. Numbers 1 to 5 were the same specimens as are enumerated in Tables 10 and 11, and were driven in filled ground containing a great deal of refuse. The rest were driven in clay and stones. The resistances given for Nos. 1 to 5 are for different pairs of driven pipes in series; that is, for 1 and 5, 2 and 5, and so on. In obtaining those for Nos. 6 to 10, the water-pipe system was employed as an auxiliary ground. Where the higher voltages were used the current was allowed to flow only while readings were being made in order to avoid heating the soil surrounding the pipes and thus changing the resistance. Nevertheless, slight changes did occur, especially at the higher voltages where readings were repeated to check for errors.

Now, none of the results given in Table 12 show discrepancies that can not be attributed to errors in measurement, or to fluctuations due to heating of the soil. Particular attention is directed toward the concordance between results obtained by the ammeter-voltmeter method and the bridge method. It appears fair to conclude, therefore, that in measuring the resistance of ground connections using alternating current the voltage makes little, if any, difference in the results.

The only way in which differences may be expected to arise is by the liberation of energy near the electrode in the form of heat if the current is allowed to flow for a considerable time. Here, if the voltage is low the rate of liberation of energy will be low, whereas if the voltage is high the rate of liberation of energy will also be high, with correspondingly greater heating of the soil. This at first causes a decrease of resistance which may amount to as much as 15 or 20 per cent, and if the rate of liberation of energy does not exceed a critical value previously discussed under the subject of dissipation of energy by ground connections, this decrease will remain in existence so long as current flows, but if the rate of liberation of energy does pass this critical value the soil will commence to dry out and an increase of resistance will follow. Hence, in making measurements of the resistance of ground connections, especially at high voltages, readings should be made immediately after the circuit is closed to avoid fluctuations of this kind. It may in some cases, of course, be desired to ascertain the fluctuations caused by heating at certain voltages, but not ordinarily, because the protective value of a ground

immediately following a failure of insulation or an accidental contact between wires depends in most cases upon the quick operating of fuses or circuit breakers, and this in turn depends upon the initial resistance.

Turning now to some of the causes for the conclusion mentioned above, viz, that the resistance of a ground connection depends upon the voltage applied, they may be summed up somewhat as follows: In the first place, where driven pipes are used it is not uncommon to find a coupling near the surface of the ground. In some cases a rather large pipe is driven in the ground, a reducer screwed on, and a small pipe taken a short distance up the pole for the purpose of placing the joint between wire and pipe out of reach of harm. The resistance of these screw joints has been found by measurement in several instances to be as much as 100 ohms. If an increasing voltage is applied to such a joint a point will be reached where the rust, red lead and oil, or other material which causes the high resistance will break down, with a sudden decrease of resistance, which may easily be taken as some phenomenon occurring in the ground connection itself rather than in the conductor leading to it. In the second place, in making tests, connection is sometimes made to fire plugs or service pipes that contain high resistance joints of the same kind as those described above, which, with a considerable voltage impressed will break down in the same way. In the third place, there is a tendency among some to reason that because in many cases when different voltages are applied to accidental grounds a decrease of resistance with increase of voltage occur, due to progressive breaking down of insulation, the same thing should occur with permanent grounds made by embedding an electrode in the soil.

But several things are here obvious: First, that the resistance of joints in pipes should in no way be considered as a part of the resistance of a ground connection. These joints should be looked upon rather as discontinuities in the ground wire or conductor and be treated as such. (See National Electrical Safety Code, rule 93, *a*.) Second, that permanent ground connections partake of very few of the characteristics of accidental grounds, and it is, therefore, a result of false reasoning to conclude that because in the one case it is not uncommonly found that a decrease of resistance occurs with an increase of voltage the same thing should be true in the other. Finally, that if the conductor leading to a ground connection is electrically continuous, it is of little moment

whether high or low voltage be employed in determining the initial resistance if the current is alternating.

(*k*) AUXILIARY GROUNDS FOR TESTING.—Where alternating current is used the making of auxiliary ground connections will not in many instances be found burdensome. When there are three or more houses or other buildings in a block in which there are lighting circuits, the ground connections already made can be utilized. If there are no existing ground connections within reach, two short pipes driven in the ground and well soaked with water will serve very well, and, if desirable, can be removed after the measurement is made. It is necessary only that sufficient current flow be obtained to give a fairly accurate reading of the

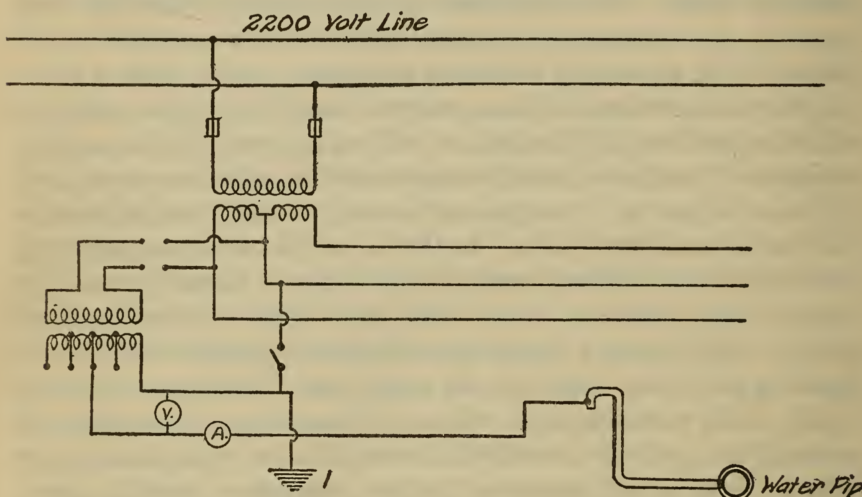

FIG. 36.—*Ammeter-voltmeter method using water pipe as an auxiliary ground*

ammeter. With direct current, however, it is best, as pointed out above, to make the resistance of the auxiliaries nearly equal to, or even less than, the resistance being measured in order to minimize the effects of polarization. The consequent difficulty in always securing suitable auxiliary ground connections constitutes a considerable disadvantage in the use of direct current for testing purposes.

It should be remarked in passing that the methods of making auxiliary grounds described in the preceding paragraph are intended to be applied only where a water pipe is not available. Where a driven pipe or plate is within reach of a water pipe, the task of making a measurement is much simplified. The resistances of nearly all water-pipe grounds are so low as to be negligible in

comparison with the resistance of driven pipes or plates, so all that is necessary to obtain a reasonably accurate measurement is to pass current through the ground to be measured and the water-pipe ground in series, as in Fig. 36, measure the total voltage, and substitute the results in the equation $R = E/I$, in the manner indicated above. Generally, no correction need be applied for the resistance of the water-pipe ground. In making such measurements, however, it is nearly always necessary to connect to the water pipe through a fire plug or a service pipe. These, in some instances, contain high resistance joints which may introduce errors, but they are not met with frequently enough to constitute a serious objection to the use of water pipes as auxiliaries. Moreover, where they are present, they usually give rise to results which are obviously in error and may be checked by means of another fire plug or service pipe. In the place of a water pipe, a bonded street-car rail may be used, since the resistance of ground connections made to these is in nearly all cases less than 1 ohm, although care must be exercised to see that stray railway currents through the ammeter are not sufficient to lead to serious discrepancies in the readings. A third means of establishing an auxiliary ground is by connecting to a grounded telephone messenger cable. The resistance to ground of these cables is usually somewhat higher than that of water pipes or bonded rails, especially bonded rails embedded in paving or soil, but they served very well where the others are out of reach.

(*l*) Leads, Clamps, and Other Accessories to Testing Outfits.—In addition to the transformers and measuring instruments previously mentioned, about 400 feet or more of single-conductor flexible cord, well insulated and mechanically protected, capable of carrying 10 amperes at least, and of known resistance per unit length, should be provided for the purpose of reaching such fire hydrants, service pipes, and other ground connections in the vicinity of the one being tested as will serve the purpose of auxiliaries. If the bridge method is employed, this cord should have a tap or pigtail every 50 feet for the purpose of making connection to binding posts, and be wound on a reel so it can be paid out or gathered in without tangling. The pigtails enable any desired length to be unreeled and be ready for use without disturbing the remainder where short distances are to be covered. It would be more convenient, of course, to bring the inner end of the wire out to a binding post and thus do away with the

necessity for pigtails, and this can be done where ammeters and voltmeters are used, but with the bridge to have a reel partly filled with wire in series with the ground connection disturbs the measurements on account of the inductance introduced. Aside from the cord just mentioned, the ammeter-voltmeter method requires in addition 100 feet of double-conductor flexible cord for

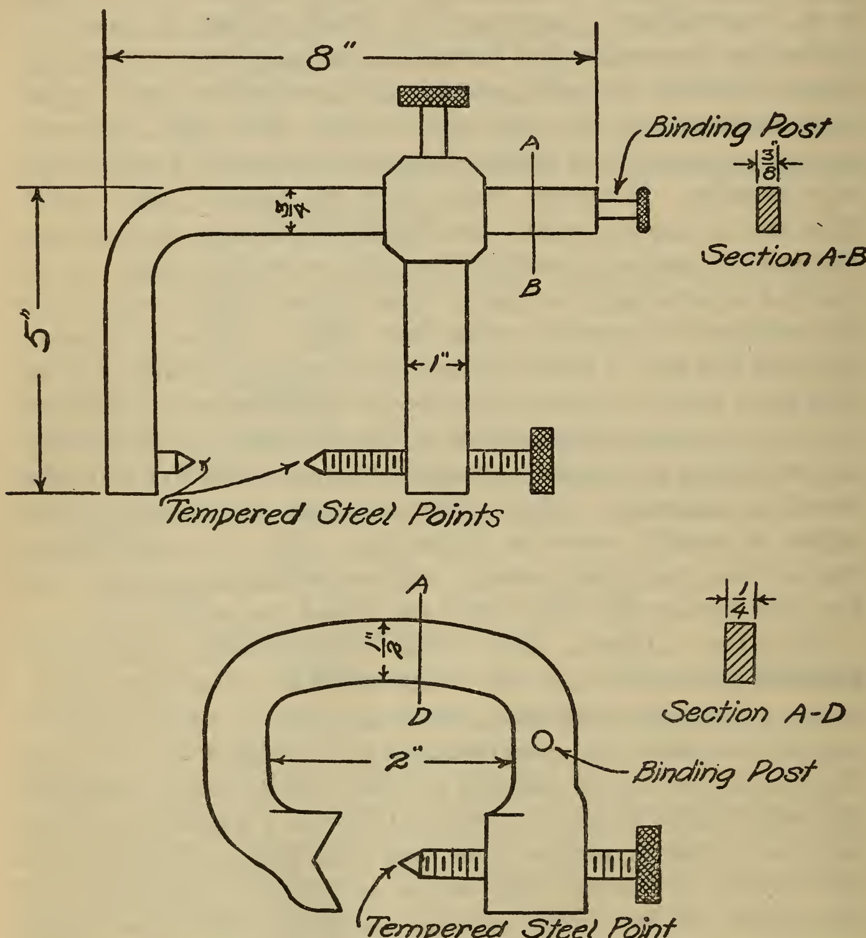

Fig. 37.—*Clamps for attaching to water pipes and ground wires*

reaching lamp sockets and service switches. These lengths will be found sufficient for nearly all cases that may arise.

For connecting wires to service pipes, fire plugs, and ground wires, two clamps are shown in Fig. 37. The larger one is designed for attaching to pipes and fire plugs, the sharp steel points being introduced for the purpose of piercing paint coatings and making

good contact with the metal. The smaller is intended for connecting to insulated ground wires. The sharp steel point easily penetrates through the insulation to the copper, and saves much time in many cases that would otherwise be consumed in skinning wires.

VII. FIRE HAZARD AND INTERFERENCE WITH SERVICE IN GROUNDING

The chief argument advanced against grounding in the past has been that it increases the fire hazard. In fact, it has been stated by many, largely on theoretical grounds, that the increase in the fire hazard is sufficient to outweigh any advantages that may follow from grounding, particular reference being had, of course, to the grounding of electrical circuits. Now such statements have at first sight an appearance of truth, for in a few cases where grounding has been resorted to as a protective measure fires have followed, but examination shows that by far the greater part of these fires have occurred in buildings where the wiring was in place for many years before grounding connections were made' and with old wiring there is undoubtedly some danger of fire unless care is taken to put the circuits in good condition before connecting them to earth. On the other hand grounding has undoubtedly averted many fires, both from high voltages on low-voltage circuits, and from leakage between accidentally grounded circuits or equipment and the earth, insufficient to blow fuses, but sufficient to cause arcing. Fires from new work, however, or even from old work which was not carelessly done in the first place, are of rare occurrence.

A second source of danger from fire or explosions is found where gas pipes are used for the purpose of grounding electrical systems. Several points concerning these two sources of danger and also the possibility that grounding may interfere with service are discussed briefly below.

1. WIRING

Where wiring which has been in place for a long time is grounded the chief difficulty encountered is that which arises from accidental grounds in buildings, trees, and other places. For a ground on one wire, which may have existed unnoticed, is likely soon to make itself apparent when another wire of the circuit is connected to earth. Current may then flow and cause fire, or at least loss of energy, unless steps are taken to ascertain the condi-

tion of the insulation and remedy any defects before damage occurs. Nevertheless, even with old work, fires do not occur with sufficient frequency to outweigh the beneficial effects, and it is likely that as many are averted as caused through the indication of accidental grounds by intentional grounding. This is shown to a considerable extent by the correspondence with electric companies previously mentioned, in which it was found that 14 companies out of 418 had experienced fires which they attributed to grounding, 182 made no statement in regard to fires, while 222 reported that no fires had occurred that could be traced to ground connections on their systems. Of the 14 companies reporting fires several had abandoned grounding entirely on account of them. Others stated that they had not commenced the practice of grounding because of doubt as to the real seriousness of the fire hazard. A large majority of the companies, however, seemed to be of the opinion that the fire hazard is negligible, and this opinion appears to be concurred in by a great many inspectors for insurance companies and others interested in the prevention of fires.

It must be admitted, however, that in earthing old work a certain amount of risk is incurred unless proper precautions are taken. In every case the insulation resistance between each wire and ground should be measured with a megger or by other means, and if the results show defects repairs should be made before the ground connection is attached. This, compared with fire losses, is a simple and relatively inexpensive procedure, and much to be preferred to earthing regardless of the condition of insulation and trusting to luck to escape the consequences of carelessness. It should be added that a circuit which shows defects by such a test constitutes a fire hazard whether grounded or not, and should be repaired.

On the other hand, with regard to the fire hazard in new work, or in old work which has been put in good condition, there is apparently no valid reason for believing that it is increased by connecting one of the circuit wires to ground. At least no reports are available which show an actual increase. Theoretically, wherever grounding necessitates increasing the strain on insulation to earth over what it would be with the circuit insulated, the fire hazard is increased because of the increased likelihood of failure of the insulation, but in low-voltage circuits this seems practically to amount to nothing. Whereas, even though there

were a large increase in the fire hazard from the low-voltage circuit, the reduction in the fire hazard from the high voltage would be more than ample to offset it. And since there is no tangible evidence that grounding does increase the fire hazard from the low-voltage circuit, the reduction in the fire hazard from high voltage appears to be all clear gain. Hence, as far as fire hazard is concerned, no good reason appears to exist for not grounding if the insulation of the low-voltage circuit is in good condition, rather there is an advantage from the standpoint of fire prevention as well as personal protection.

2. GAS PIPES

In grounding as it is practiced at present, considerable use is made of gas pipes. This is due in some cases to the fact that the electric companies own the gas systems. In others the use of the water pipes is forbidden, while that of the gas pipes is not. Now, there are several reasons why it is inadvisable to use gas pipes for making ground connections unless it be in special cases. In the first place, current flow in them is dangerous, for if a disconnection is made a spark may follow, and even a small spark may cause a fire or an explosion. In the second place, in laying them, cement or other insulating joints are used to a large extent, and the ground connection may, therefore, be poor and not of such a character as to give the required protection to life and property. And in the third place, where there are gas pipes there are in nearly all cases water pipes, making connection to the gas pipes unnecessary. In view of these facts connection to gas pipes should be avoided except in those cases where current flow through the ground connection is extremely unlikely to occur, or where other grounds are not available. Moreover, even in such cases care should be exercised to see that the pipe is electrically continuous for some distance into the ground and the ground connection of sufficiently low resistance to give the required protection. The cases in which grounding to gas pipes may be permissible include chiefly the noncurrent-carrying parts of small motors, electric-lighting fixtures, and other appliances in which, on account of fuses or other protective devices of low-current rating, a heavy flow of current to ground is practically impossible, and even a light flow unlikely, but for grounding electrical circuits the use of gas pipes should be prohibited.[44]

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[44] See rule 94*a*, Appendix II.

On the other hand, it may perhaps be well to repeat at this point the statement that grounding to water pipes should not only be permitted, but be made compulsory, especially where safety to the public is involved. For it has been shown that such connection obviates both a life and a fire hazard that might otherwise arise when lightning or other cause destroys transformer insulation or wires become crossed. Inasmuch as it causes no appreciable disadvantage to either of the public-service companies concerned and both contribute to the life hazard by introducing pipes and circuits into buildings in many cases in close proximity to each other, there seems to be no good reason why city ordinances or other legislation to require it should be longer delayed. In numerous localities, the practice has been tried and found desirable, some statutes and ordinances have been passed requiring it, and it should be extended to all places where high-voltage alternating-current distribution systems are in use.

3. INTERFERENCE WITH SERVICE

In addition to the question of fire hazard, it has also been stated by some that grounding interferes with service; that is, in a circuit which is connected to earth a single accidental ground may cause a fuse to blow and interrupt the flow of current, whereas if the ground connection were omitted such an accidental ground might exist indefinitely without affecting the conditions of operation. This, of course, is true; but as in the case of fire hazard, experience has not shown that it is a factor that needs seriously to be reckoned with on account of the infrequency with which accidental grounds appear in low-voltage circuits except through careless work. Interference with service through accidental grounds on permanently grounded circuits may, therefore, be regarded rather as an argument against poor work than against grounding. Moreover, although it is true that a single accidental ground on a grounded circuit may lead to inconvenience, it is also true that where ground detectors are not used such a ground on a circuit which is not permanently grounded may exist *unnoticed* until a second ground occurs on the opposite wire, in which case the trouble would be no less than in the other, and might be worse, because by the time the fault made itself known there would be two accidental grounds of which either one or both might be in an inaccessible place. So for practical purposes the possibility of trouble from accidental grounds on grounded circuits can be considered as quite offset by the possibility of similar trouble arising with circuits which are not grounded.

VIII. COSTS

At the present time very little information is available in regard to the cost of making ground connections. This is due, in part at least, to the fact that many companies when grounding newly installed circuits include the outlay for the labor and materials required in the total cost of the installation. Others include it in maintenance, or under other heads, evidently considering the expense too small to justify the keeping of a separate account. In the correspondence with electric companies, previously referred to, a question was asked concerning the making of ground connections, and in reply 59 put the cost at from $1 to $2; 107, from $2 to $5; 23, from $5 to $10; and 5 at more than $10. Most of these figures, however, were specifically stated to be estimates. Moreover, there is no way of telling whether all of the charges which should have been included were taken into consideration. There is, therefore, some question as to the reliance which should be placed upon them. This doubt gains added force from the fact that other sources of information,[45] instead of putting the cost from $2 to $5, as did the majority of the replies quoted above, placed it from $6 to $15, which may or may not be higher than average costs. It should be added that 66 companies expressed themselves definitely to the effect that they grounded low-voltage alternating-current circuits, but made no mention as to their expenditures for grounding.

The chief causes for the foregoing great differences in cost lie, of course, in the character of the ground connection used, the kind of soil in which it is situated, the thoroughness with which the work is done, and also the items charged to the account of grounding. Where water pipes are used, the least expensive protection probably is obtained, although if a long run of wire is required, or much excavation, the cost may be as great as for other types. The connections which in general involve the smallest amount of labor and materials are those to service pipes. For these one company reports an average outlay of $2.05, this average being based on the installation of a large number at a time. Where only a few are to be made, however, the expense would be somewhat greater. One company stated that the cost ranged from $5 to $15, being somewhere near the lower figure where the circuit to be grounded enters the basement of a house, and somewhere near the higher figure where the circuit enters the attic,

[45] Electrical World, 49, p. 906; 55, p. 1012; 59, p. 1352; 59, p. 1215.

but it is likely that the higher figure would be found to apply only in extraordinary cases. For ground connections of other types the estimated cost ranges between as wide limits as for water pipes. In actual practice, however, the total cost may be expected to run uniformly higher. The increase amounts practically to that caused by the materials for the elctrode and the labor of embedding it in the ground. The only possibility of an offset to this increase lies in shortening the ground wire. That is, it often occurs that in making a connection to a service pipe a considerable distance has to be covered to reach the point of attachment to the circuit, whereas if a driven pipe or a plate is used it is nearly always practicable to locate it at a point which is much more convenient, and in that way a part of the expenditure of labor and materials which would otherwise be necessary in installing the ground wire may be saved. The saving in most cases, however, is too small to be of much moment.

With regard to maintenance the replies received were even more unsatisfactory than in respect to installation. Ten reported the average cost of maintenance as being from 10 to 25 cents per year; 17, from 25 cents to $1; 1, from $1 to $3; and 1, from $3 to $5. The rest, or 231 of the 260, stated that they grounded low-voltage alternating-current circuits, but had nothing to say as to maintenance.

It is practically impossible from these data to obtain more than a rough idea of the cost of making and maintaining ground connections. To make anything like a dependable statement requires that much more data be collected. Such data should cover the cost per unit length of running ground wires and protecting them from mechanical injury, of materials for electrodes and embedding them in different soils, and of making joints both to water pipes and to electrodes of other forms. With these points well covered a fairly accurate statement of cost could be made, which is very desirable where an entire system is to be grounded, or in any case where a considerable outlay for grounding is contemplated.

IX. BASES FOR SPECIFICATIONS

That the physical characteristics of ground connections should receive careful attention when specifications are written is evident from the foregoing discussion and experimental results, but particular instances of the lack of such attention in the past are found in many of the codes of rules concerning electrical construction

which are at present operative in the United States. In fact, the majority of these codes require no proof whatever of the fitness of a ground connection to serve the purpose for which it is installed. The tendency shown in their compilation has been to prescribe the form of ground connection to be used rather than the results that it shall be made to produce, which is the exact opposite of the tendency shown in many countries of Europe. The chief objections to an arbitrary ruling in this respect are based upon facts previously discussed in this paper, viz, that there is a great degree of variation in soil and moisture conditions from place to place, and also that there is a great degree of variation in the requirements placed upon ground connections for different purposes. As a consequence a form that will give satisfactory results in one place may give extremely unsatisfactory results in another place. Hence, in making specifications it is best to formulate the results which it is necessary to produce and leave the means to be used to be decided according to the facts and circumstances surrounding each case. This requires that the limiting values of at least the most important physical characteristics be designated.

Now, as already shown, in nearly all cases where ground connections are used their purpose is to prevent an unsafe rise of potential against ground of the system which they are intended to serve. This, in general, involves a flow of current of greater or less intensity, so resistance is the characteristic that must be given the greatest weight. That is, the degree of safety provided by a ground connection depends upon its resistance, which, unless conditions make it impracticable, must always be such that with the current flow to earth at the maximum value that it is likely to reach in the event of an accident to insulation, the potential difference temporarily existing between the grounded wire and any point on the ground shall not be high enough to be dangerous. Where persons may come in contact with circuits, or apparatus or appliances connected to them, this potential difference, for a good degree of safety, should certainly not much exceed 150 volts. On the other hand, where circuits and apparatus are inaccessible, and the chief danger presented is that to insulation between circuits and ground, higher voltages may be allowed. These, of course, are aside from the potential differences normally existing between the ungrounded wires of a circuit and ground due to the voltage of the circuit itself, which have little to do with

determining the resistance of the ground connection, the latter being determined almost entirely by the possible current flow in the ground wire and voltage rise between circuit and ground which may originate in accidental crosses or contacts with high-voltage lines.

As indicated above, many cases will be encountered where for a good degree of safety it will be necessary that the resistance be low enough to prevent the appearance of potential differences between grounded wire and ground from high-voltage lines exceeding 150 volts. It may happen, however, that soil conditions are so bad as to prevent obtaining a resistance which is sufficiently low for the purpose, or it may be that during certain seasons of the year drought or frost causes the resistance to reach very high values. Under such circumstances it will often be necessary to depend for safety partly or wholly upon other measures than grounding, or at least upon supplementary measures. An example of supplementary measures which may be resorted to is found in the isolation of fixtures and appliances, or in putting them where they can not be touched, except when the body is insulated from the ground. Another example is in the use of insulated coverings on the grounded circuit wires and even the ground wires themselves.

Another characteristic which should receive attention is capacity to dissipate energy. As to this there must be reasonable assurance that under normal conditions of moisture a ground connection will carry for a considerable period, without an increase of resistance, the maximum current that is likely to flow. Reasonable assurance, however, is about all that can be required in this respect. For, in the first place, so much depends upon the moisture content of the soil, and, in the second place, so much time and electrical energy must be expended in making tests that to specify rigorously the capacity of a ground connection to dissipate energy would in all but a few cases lead to greater expense than the results would justify. Attention to the extent of testing need be required only where the current flow may be of the order of hundreds of amperes, and where at the same time the resistance is not as low as it should be. In general, it may be stated that if the safety requirements in regard to resistance are complied with, especially safety to life, the capacity to dissipate energy may be taken as sufficient. Water-pipe grounds may be reckoned as almost universally satisfactory, but artificial grounds, unless in multiple, may in many cases be unsatisfactory.

Likewise, as far as potential gradient is concerned, if the resistance is sufficiently low for safety, there is slight danger to persons from potential differences in the ground. There is, however, a source of danger in potential differences between ground wire and ground, but to avert it all that is necessary is to cover the wire with insulating material as indicated previously in this paper. Animals, on the other hand, are very susceptible to electric shocks, and much trouble will be avoided if it is required that where there is a possibility of such trespassers coming near ground connections the immediate vicinity be made inaccessible to them by fencing or other means.

In conclusion, long life of the ground connection is very desirable and should be given special consideration in making specifications. To this end the construction should be made very substantial, as emphasized heretofore. The materials used should not present galvanic couples at joints, or, if they do, corrosion should be prevented by painting, coating with tar or pitch, or embedding in concrete. The means employed for reducing the normal resistance should not be extraordinarily detrimental to the electrode. Moreover, such means should be allowed only where adequate inspection and repairs are made; otherwise there is small assurance that salt, for instance, will be renewed when its effects wear away.

With these points well covered fair results may be expected, but at the same time it should be remarked that the available data upon which specifications may be founded are incomplete. Much more information is necessary before grounding, at least to artificial grounds, can be placed upon as sound a basis as is desirable. This information should comprise resistance, capacity to dissipate energy, variation of resistance with seasons, the period required for the effect of salt and other substances to wear away, the life of the electrodes, and costs, both of installation and maintenance, in soils of all kinds. Moreover, the performance of ground connections in service should be noted at every opportunity, and a record made of their electrical characteristics. In the course of time much valuable information could be accumulated in this way which would be of great assistance in safeguarding life and property from electrical dangers. To begin this task, the Bureau of Standards has recently sent a representative to cities in different sections of the country to measure the resistances of a large num-

30263°—18——12

ber of such artificial ground connections as are now used for protective purposes. The results of these measurements are tabulated and discussed below.

X. FIELD MEASUREMENTS OF THE RESISTANCE OF ARTIFICIAL GROUND CONNECTIONS

The results of field measurements made up to the present time are set forth in Table 13, which shows the cities visited, the types of grounds tested, the kind of soil in which the electrodes were embedded, the auxiliary grounds used, and, in the last column, the resistances. The cities named were selected mainly because it was known that in them driven pipes, plates, or grounds of forms other than water pipes were used either exclusively or to a considerable extent. In making the selection an attempt was also made to include points in some of the New England States, the Middle Western States, and the Rocky Mountain States.

TABLE 13.—Resistance of Ground Connections

NEWARK, N. J.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	1½-inch driven pipe, 10 pounds salt.	6	Red clay	Water pipe	2.5
2	....do	6	....do	....do	22
3	....do	6	....do	....do	2
4	....do	6	Red clay under building, dry.	....do	800
5	....do	6	Clay and loam in sump of garage.	....do	7
6	....do	6	Clay and loam wet with brine.	....do	3.5
7	....do	6	Clay, rather dry	....do	42
8	....do	6	Low, marshy	....do	3
9	....do	6	....do	....do	3

PATERSON, N. J.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	Two 1½-inch pipes driven 6 inches apart.	6	Stony clay and loam	Measured by 3-point method.	404
2	½-inch driven pipe in cellar	8	....do	....do	268
3	Driven well, size of pipe and depth not known.	....	Stony clay	....do	20
4	Steel trolley poles set in concrete.	5	Sandy	Two poles in series	310
5	....do	5	....do	....do	700

TABLE 13.—Resistance of Ground Connections—Continued

ELIZABETH, N. J.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	$1\frac{1}{4}$-inch driven pipe, 10 pounds salt.	6.5	Shale	Water pipe	22
2	do	9	Red clay and shale	do	12
3	do	9	do	do	15
4	do	9	Red clay	do	19
5	do	10	Sand and gravel, dry	Bonded rail	190
6	do	10	Wet sand and gravel, marshy.	Water pipe	41
7	do	10	Red clay and gravel, dry	Two pipes in series	160
8	do	7	Red clay, some gravel	Bonded rail	40
9	do	10	Red clay, beside ditch	do	4.5
10	do	10	do	Water pipe	8

NEW YORK CITY, BRONX DISTRICT

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	3-inch service stand pipe 35 feet long.	3	Ground low	Water pipe	6.5
2	do	3	do	do	6
3	do	3	Gravelly	Bonded rail	10
4	do	3	Stony, on hill	Water pipe	20
5	do	3	do	do	45

PROVIDENCE, R. I.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	$\frac{3}{4}$-inch driven pipe	10	Gravel and sand	Water pipe	260
2	do	10	Gravel and clay	Bonded rail	70
3	do	10	Gravel	Water pipe	2500
4	do	10	Gravel and sand	In series with a number of grounds at other points, 4 at least.	1700
5	do	10	Stones, gravel, sand	Measured by 3-point method.	2700
6	do	8	do	do	1300
7	Local water system, driven well, 100-foot pipe.		do	do	300
8	$\frac{3}{4}$-inch driven pipe	10	Gravel and sand	Water pipe	700
9	do	10	do	do	250
10	do	10	do	do	800
11	do	10	3 feet loam over fine sand	do	115
12	do	10	Gravel	do	630
13	do	10	do	do	1300
14	do	10	Sandy	do	800
15	do	10	Gravel	do	1100
16	do	10	do	Several other grounds on neutral.	370
17	do	10	do	Two grounds in series	1300
18	do	10	do	Other grounds on neutral	900
19	2-inch driven pipe, substation ground.	20	do	Water pipe	30
20	$\frac{3}{4}$-inch driven pipe	10	Gravel and sand on hill	Bonded rail	2700
21	do	10	Gravel and sand, stones	Other grounds on neutral	1100

TABLE 13.—Resistance of Ground Connections—Continued

NEW HAVEN, CONN.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	Four ¾-inch pipes driven 18 inches apart.	8	Gravel and sand	Common ground wire	170
2	¾-inch driven pipe	6	Gravel and sand in damp cellar.	do	250
3	Local water system, 50-foot pipe.	3	Gravel and sand	do	40
4	Local water system, 100-foot pipe.	3	do	do	15
5	¾-inch driven pipe	8	do	do	920
6	do	8	Gravel, sand, clay	do	170
7	do	8	do	Bonded rail, also common ground wire.	85
8	do	8	Gravelly	Bonded rail	160

BOSTON, MASS.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	1¼-inch driven pipe, perforated, patented device.	6	Sandy dry	Neutral grounded at 3 other places.	700
2	2-inch driven pipe	10	do	In series with 50-foot service to cement water main.	1400
3	do	40	Swampy ground	Messenger of telephone cable.	25
4	Local water system, 700-foot pipe.	3	Gravelly	Bonded rail	14
5	1-inch driven pipe	6	Gravel and sand	do	880
6	Copper plate in cesspool	8	Gravel and sand over rock.	do	30
7	2-inch driven pipe	10	Gravel and sand	Measured by 3-point method.	950
8	Local water system, 100-foot pipe.	3	do	do	1150
9	Pole guy	5	do	do	2250
10	2-inch driven pipe	20	Sandy, moist, in draw	Water pipe	105
11	do	6.5	Gravelly, pipe driven to rock.	do	1100
12	do	4.5	Gravelly, dry around pipe.	do	2100
13	Three 2-inch pipes driven touching each other in wet manhole.	12	Gravel and clay	do	23
14	Three 2½-inch pipes driven touching each other in wet manhole.	10	do	do	19
15	2½-inch pipe in bottom of 8-foot manhole.	12	do	do	13
16	2½-inch pipe in bottom of 8-foot manhole, salted.	24	do	do	65
17	2-inch pipe in 6-foot manhole.	10	do	do	38
18	1-inch pipe in 6-foot manhole.	6	do	do	45
19	do	6	do	do	46
20	Plate 2 feet square	6	Low ground covered with stable refuse.	do	7

TABLE 13.—Resistance of Ground Connections—Continued

PHILADELPHIA, PA.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	2-inch driven pipe	4	Low ground	Water pipe	16
2	....do	6	....do	....do	17
3	....do	6	....do	....do	29
4	....do	6	Low ground near Delaware River.	....do	40
5	....do	6	Low ground	....do	23
6	....do	6	....do	....do	16
7	....do	6	....do	....do	21
8	....do	5	Filled ground, cinders, slate.	3-point method	5
9	....do	6	Low ground	Water pipe	23
10	....do	6	....do	....do	21
11	....do	6	....do	....do	32
12	....do	6	....do	....do	28
13	....do	6	....do	....do	26
14	....do	6	....do	....do	12
15	....do	6	....do	....do	17
16	....do	6	Clay and stones, rather high.	....do	180
17	....do	6	Low ground	....do	15
18	....do	6	Clay	....do	42
19	....do	6	Clay and stones, high ground.	....do	65
20	....do	6	....do	....do	130
21	....do	6	....do	150-foot water service to cement main.	170
22	....do	6	High stony ground	Water pipe	330
23	....do	6	....do	....do	1400
24	....do	6	High ground, clay and stones.	....do	430
25	....do	6	....do	....do	390
26	....do	6	....do	....do	101
27	....do	6	High and stony	....do	210
29	....do	6	....do	....do	105
30	....do	6	....do	....do	165
31	....do	6	....do	....do	115
32	....do	6	....do	Bonded rail	65
33	....do	6	Clay, high	....do	55
34	....do	6	Clay and stones, high	....do	450
35	....do	6	do	....do	380
36	....do	6	Clay wet by waste water.	Water pipe	13.5
37	....do	6	Clay and gravel	Bonded rail	200
38	....do	6	Clay, low	Water pipe	23
39	....do	6	....do	....do	38
40	....do	6	....do	Bonded rail	27
41	....do	6	Clay	Water pipe	75
42	....do	6	Clay and sand	....do	110

TABLE 13.—Resistance of Ground Connections—Continued

SCRANTON, PA.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	1-inch driven pipe	5	Clay and gravel	Water pipe	135
2	do	5	do	do	95
3	do	5	do	do	100
4	do	5	do	do	240
5	do	5	Gravelly	do	350
6	do	5	do	do	195
7	do	5	do	do	19
8	do	5	do	do	135
9	do	5	Gravelly, top of knoll	do	490
10	do	5	Gravelly, stony	do	40
11	do	5	do	do	95
12	do	5	do	do	100
13	do	5	do	do	71
14	do	5	do	do	155
15	do	5	do	do	155
16	do	5	do	do	85
17	do	5	do	do	300

OMAHA, NEBR.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	Hydroground	6	Yellow clay	Water pipe	20
2	do	6	do	do	60
3	do	6	do	do	37
4	do	6	do	do	55
5	do	6	do	do	29
6	do	6	do	do	18
7	do	6	do	do	22
8	do	6	do	do	19
9	do	6	do	Bonded rail	10
10	do	6	do	Water pipe	35
11	do	6	do	do	19
12	do	6	do	do	25
13	do	6	do	Bonded rail	33
14	do	6	do	Water pipe	11
15	do	6	do	Bonded rail	35
16	do	6	do	do	27
17	Plate 18 by 24 inches in small amount of charcoal	6	do	Water pipe	30
18	do	6	do	do	28
19	do	6	do	do	29
20	1 inch driven pipe	10	do	do	6.5
21	Two 1-inch driven pipes 6 inches apart.	10	do	do	11.0
22	1-inch driven pipe	10	do	Bonded rail	12
23	do	6	do	do	35
24	do	10	Yellow clay, high, rather dry.	do	45
25	do	10	Yellow clay	do	14
26	do	10	Yellow clay, hollow, water settles.	do	6
27	do	10	Yellow clay	Water pipe	21

TABLE 13.—Resistance of Ground Connections—Continued

OMAHA, NEBR.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
28	1-inch driven pipe in parallel with steel pole.	10	Yellow clay	Bonded rail	14
29	.....do	10	.....do	.....do	5
30	1-inch driven pipe	10	Yellow clay, very wet, broken water main.	.....do	3.5
31	.....do	10	Yellow clay	.....do	4.5
32	.....do	10	.....do	Water pipe	7.0
33	.....do	10	.....do	.....do	9.0

DENVER, COLO.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	1-inch driven pipe	8	Clay over sandy loam	Water pipe	25
2	Coil No. 4 wire at base of pole.	6	Clay	.....do	15
3	1-inch driven pipe	8	.....do	.....do	45
4	.....do	8	Loam over gravel	.....do	125
5	.....do	8	Coarse gravel	.....do	190
6	.....do	8	Sandy soil over gravel	.....do	48
7	.....do	8	Clay	.....do	17
8	.....do	8	Gumbo	.....do	7
9	.....do	8	Clay over sand	.....do	28
10	.....do	10	Sandy loam	.....do	15
11	.....do	8	Sandy loam and gumbo	.....do	45
12	.....do	8	Gravel and gumbo	.....do	18
13	.....do	8	Gravelly	.....do	55
14	.....do	8	.....do	.....do	72
15	.....do	8	Gumbo over gravel	.....do	52
16	Paragon cone	6	Gravelly	.....do	210

COLORADO SPRINGS, COLO.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	1-inch driven pipe	8	Gravel	Water pipe	200
2	.....do	8	Sand and gravel	.....do	350
3	.....do	8	Adobe	.....do	90
4	.....do	8	.....do	.....do	16
5	1-inch driven pipe with arc light carbons around it.	8	Red sand	.....do	14
6	1-inch driven pipe	8	Adobe and gravel	.....do	85
7	.....do	8	Sand	.....do	63
8	.....do	8	.....do	.....do	35
9	.....do	8	Sandy	.....do	13
10	.....do	8	Adobe	.....do	55

PUEBLO, COLO.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	¾-inch driven pipe	18	6 feet of dump over sand.	6-inch driven well	4.5
2	.....do	18	.....do	.....do	3.5
3	.....do	6	Adobe and stones	Water pipe	210
4	.....do	8	Adobe with some gravel.	.....do	35
5	.....do	12	.....do	.....do	46

TABLE 13.—Resiatance of Ground Connections—Continued

PUEBLO, COLO.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
6	Four ¾-inch pipes driven 6 feet apart.	12	Sandy	Water plpe	15
7	¾-inch driven pipe	6	do	do	75
8	do	6	do	do	7
9	do	6	do	do	65
10	do	6	Filled ground	do	12
11	do	6	do	do	14
12	do	6	do	do	8
13	do	6	do	do	8
14	do	6	Adobe	do	13
15	do	6	do	do	33
16	do	8	do	do	18
17	do	8	Adobe wet from exhaust pipe.	do	14
18	do	8	Adobe	do	77
19	do	6	do	do	25
20	do	6	do	do	13
21	do	6	Sandy	do	26
22	do	6	do	do	60

LEADVILLE, COLO.

1	Coil No. 0 stranded wire in bushel of charcoal.	8	Stony, side hill	Water column in mine	200
2	do	8	Sandy, wet by waste from stamp mill.	Water pipe, running under stamp mill.	33
3	do	8	Stony, with sand and clay.	Water pipe	53
4	do	8	Stony, beside wet gutter	do	137
5	do	8	Stony, near old ash pile	do	25
6	¾-inch driven pipe	8	Stony	do	44
7	Coil No. 1 wire in charcoal	8	do	do	28
8	¾-inch driven pipe	6	Stony, in ash pile	do	48
9	Coil No. 1 wire in coke	8	Stony	do	42

SALT LAKE CITY, UTAH

1	Two ¾-inch pipes driven 2 feet apart.	8	Black loam 5 feet deep over gravel, low.	Water pipe	5.5
2	do	8	do	do	13
3	¾-inch driven pipe	8	Black loam over gravel	do	15
4	do	6	Dry, stony soil, on bench	do	140
5	do	8	do	do	93
6	do	7	do	do	105
7	do	8	Sand, gravel, clay	do	18
8	do	7	Gravelly, on bench	do	210
9	do	8	Stony, on bench	do	86
10	do	8	do	do	115
11	do	7	Very stony, on bench	do	210
12	Two ¾-inch pipes, driven 3 feet apart.	8	Sandy, rather low	do	9

TABLE 13.—Resistance of Ground Connections—Continued

SALT LAKE, CITY, UTAH—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
13	Two ¾-inch pipes, driven 18 inches apart.	8	Cinder dump, low ground	Water pipe	5.5
14	¾-inch driven pipe	8	Gumbo over sand	do	10.5
15	do	8	do	do	17
16	do	8	do	do	14
17	do	8	Adobe with some stones.	Bonded rail	18
18	do	8	Gravelly	Water pipe	25

BUTTE, MONT.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	½-inch pipe driven in bottom of post hole.	4	Wash sand, decomposed granite.	Water pipe	380
2	Coil of No. 4 wire at foot of pole.	5	Wash gravel	do	240
3	do	5	Wash sand, decomposed granite.	do	145
4	¾-inch driven pipe	7	do	do	140
5	⅝ driven rod	7	do	do	140
6	do	7	do	do	160
7	Coil of No. 0 wire at foot of pole.	5	Clay	do	55
8	Coil of No. 4 wire at foot of pole.	5	Gravel and sand	do	65
9	do	5	Dump from mine	do	42
10	do	5	Dump; rock, cinders, sand	Bonded rail	33
11	do	5	Clay and stones	Water pipe	85
12	do	5	Decomposed granite and stones.	do	78
13	do	5	Filled ground	do	18
14	do	5	Decomposed granite, stones.	Bonded rail	111
15	do	5	Tailings from smelter, damp.	do	17
16	do	5	Sandy	Water pipe	140
17	do	5	Stony side hill	do	80
18	do	5	Silt and sand	Bonded rail	92
19	do	5	Sand and stones	Water pipe	57
20	do	5	Sandy	do	140
21	do	5	Decomposed granite	Bonded rail	140

HELENA, MONT.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	1-inch driven pipe, about 3 pounds salt.	8	Decomposed limestone, stones.	Water pipe	36
2	do	6	do	do	205
3	do	8	do	do	48
4	do	8	do	do	65
5	do	8	do	do	155
6	do	8	Stony	do	105

TABLE 13.—Resiatance of Ground Connections—Continued

HELENA, MONT.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
7	1-inch driven pipe, about 3 pounds salt.	8	Decomposed limestone, stones.	Water pipe	38
8	do	8	do	do	55
9	do	8	do	do	50
10	do	8	do	do	88
11	do	8	Clay and stones	do	21
12	do	8	do	do	45
13	do	8	do	do	34
14	do	7	do	do	160
15	Two 1-inch driven pipes, about 3 pounds salt.	8	do	Bonded rail	45
MOORHEAD, MINN.					
1	¾-inch driven pipe	7	Black loam over clay	Water pipe	7
2	do	7	do	do	35
3	do	7	do	do	19
4	do	7	do	do	14
5	Paragon cone	6	do	do	21
6	½-inch driven pipe	7	do	do	90
7	Paragon cone	6	do	do	45
8	¾-inch driven pipe	7	do	do	11
9	do	7	do	do	50
10	1-inch driven pipe	7	do	Bonded rail	13
11	½-inch driven pipe	7	do	do	55
12	Paragon cone	6	do	Water pipe	11
MINNEAPOLIS, MINN.					
1	1-inch driven pipe	7	Gravelly	Water pipe	46
2	¾-inch driven pipe	10	do	do	240
3	do	8	do	do	27
4	do	7	do	do	210
5	do	8	do	do	490
6	do	8	do	do	320
7	1-inch driven pipe	8	do	do	59
8	¾-inch driven pipe	8	Gravel, clay, sand	do	260
9	do	8	Filled ground	do	28
10	Two 1-inch driven pipes near each other.	8	Gravel	do	155
11	1-inch driven pipe	8	Clay and stones	do	57
12	do	8	Black loam over sandstone.	do	16
13	¾-inch driven pipe	8	Stony	do	340
14	1-inch driven pipe	8	do	do	80
15	¾-inch driven pipe	8	Clay	do	98
16	do	8	do	do	72
17	do	8	do	do	32
18	do	8	Gravelly	do	105
19	do	8	Filled ground	do	7

TABLE 13.—Resistance of Ground Connections—Continued

MINNEAPOLIS, MINN.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
20	1-inch driven pipe	8	Filled ground	Bonded rail	17
21	¾-inch driven pipe	8	Sandy	Water pipe	120
22	do	8	do	do	59
23	1-inch driven pipe	8	do	do	75
24	¾-inch driven pipe	8	do	do	110
25	do	8	Filled ground	do	21
26	do	8	Sandy	do	85
27	1-inch driven pipe	8	do	do	130
28	¾-inch driven pipe	8	Clay and sand	do	29
29	do	8	Clay and stones	do	12
30	1-inch driven pipe	8	do	do	66
31	¾-inch driven pipe	8	do	do	95
32	1-inch driven pipe	8	Loam over sand	do	28
33	¾-inch driven pipe	8	Sandy	do	260
34	do	8	Sand, gravel, loam	do	125
35	do	8	do	do	77
36	½-inch driven pipe	8	do	do	145

DES MOINES, IOWA

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	1-inch driven pipe	9	Filled ground	Water pipe	6
2	⅝-inch driven rod	8	Black, low, and wet	do	28
3	1½-inch driven pipe	8	Clay	do	14
4	do	9	do	do	9
5	do	9	do	do	10
6	do	9	do	do	6.5
7	do	10	do	do	12
8	do	9	Sandy loam, swampy	do	12
9	do	9	Clay	do	10.5
10	do	9	do	do	6

DAVENPORT, IOWA

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	1-driven pipe	10	Clay	Water pipe	7.5
2	do	10	do	do	14
3	do	10	do	do	13
4	do	10	do	do	10
5	do	10	do	do	5.5
6	do	10	Black loam over clay	do	8
7	do	10	Sandy	do	25
8	Coil of wire at foot of pole	5	Black soil	do	13
9	1-inch driven pipe	10	Clay	do	8
10	do	10	do	do	7
11	do	10	Black loam over clay	do	11
12	do	10	Clay	do	6
13	do	10	do	do	10

TABLE 13.—Resistance of Ground Connections—Continued

PEORIA, ILL.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	Maxum ground box	8	Clay	Water pipe	9
2	$\frac{1}{2}$-inch driven pipe	8	do	do	14
3	$\frac{3}{4}$-inch driven pipe	8	Loam over clay	do	55
4	do	8	Clay	do	25
5	do	8	Sandy	do	45
6	$\frac{1}{2}$-inch driven pipe	8	Sand and gravel	do	52
7	do	8	do	do	38
8	$\frac{3}{4}$-inch driven pipe	8	Sand	do	64
9	do	8	Sandy	do	34
10	$\frac{1}{2}$-inch driven pipe	10	Sand	do	70

CHICAGO, ILL.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	$\frac{1}{2}$-inch driven pipe	8	Sandy	Water pipe	37
2	do	8	do	do	26
3	do	8	do	do	26
4	do	8	do	do	16
5	do	8	do	do	43
6	do	8	Black loam over sand	do	15
7	do	8	do	do	14
8	do	8	Clay	do	7
9	do	8	do	do	10
10	do	8	do	do	10
11	do	8	do	do	8

MILWAUKEE, WIS.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	$\frac{5}{8}$-inch driven pipe	6	Black soil, low	Water pipe	18
2	$\frac{3}{8}$-inch driven pipe	6	Gravel and clay	do	46
3	$\frac{5}{8}$-inch driven pipe	6	Sand and gravel	do	72
4	do	6	Clay and gravel	do	58
5	do	6	Sand and clay	do	85
6	do	6	Red clay	do	42
7	do	6	Clay and gravel	do	40
8	do	6	Gravel and clay	do	38
9	do	6	Clay and gravel	do	52
10	do	6	do	do	33
11	do	6	Blue clay	do	43
12	do	6	Clay and gravel	do	25
13	do	6	Clay	do	15
14	do	6	do	do	27
15	do	6	do	do	45
16	do	6	do	do	29
17	do	6	Gravelly clay	do	43
18	do	6	Red clay and gravel	do	25
19	do	6	do	do	35

TABLE 13.—Resistance of Ground Connections—Continued

INDIANAPOLIS, IND.

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	¾-inch driven pipe	8	Clay and gravel	Water pipe	72
2	do	8	do	do	36
3	do	8	do	do	140
4	do	8	do	do	66
5	do	8	Gravel	do	150
6	do	8	Clay	do	19
7	do	8	do	do	13
8	do	8	do	do	28
9	do	8	do	do	27
10	do	8	do	do	22
11	do	8	Clay and gravel	do	28
12	do	8	do	do	64
13	do	8	Clay	do	72
14	do	8	Clay and gravel	do	108
15	do	8	do	do	76

CINCINNATI, OHIO

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	Federal cartridge grounds, 4 in parallel.	6	Sandy	Water pipe	10
2	Paragon cones, 5 in parallel	6	Sandy, on bank of canal	do	5
3	Paragon cones, 3 in parallel	6	Sandy	do	7
4	⅝-inch driven pipe	6	Rocky	do	200
5	do	6	Stony	do	22
6	do	6	Gravel and clay	do	65
7	do	6	do	do	70
8	do	6	Clay	do	31
9	do	6	do	do	27
10	do	6	do	do	15
11	do	6	Clay and stones	do	37
12	do	6	do	do	51
13	do	6	Clay	do	40
14	do	6	do	do	15
15	do	6	do	do	21
16	do	6	Filled ground	do	17
17	do	6	Clay and stones	do	18
18	do	6	do	do	38
19	do	6	Clay	do	11
20	do	4	Clay and stones	do	93

DAYTON, OHIO

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	¾-inch driven pipe	6	Gravelly	Water pipe	105
2	do	6	Gravelly, moist	do	36
3	do	6	do	do	48
4	do	6	do	do	115
5	do	6	Filled ground	do	41
6	do	6	do	do	24
7	Paragon cone	6	Sandy	do	52
8	Coil of messenger wire	6	do	do	13
9	¾-inch driven pipe	6	do	do	85

TABLE 13.—Resistance of Ground Connections—Continued

DAYTON, OHIO—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
10	¾-inch driven pipe	6	Filled ground	Bonded rail	19
11	.....do	6	.....do	.....do	32
12	.....do	6	Clay	Water pipe	26
13	.....do	6	.....do	.....do	28
14	.....do	6	.....do	Bonded rail	48
15	.....do	6	Clay over gravel	.....do	22
16	.....do	6	.....do	Water pipe	44
17	.....do	6	Gravelly	.....do	45
18	.....do	6	Filled ground, bank of canal.	.....do	55
19	.....do	6	Gravelly	.....do	90
20	.....do	6	Stony	.....do	25
21	2 by 4 foot copper plate below water level.	12	Gravelly	.....do	48

TOLEDO, OHIO

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	¾-inch driven pipe	12	Clay	Bonded rail	8
2	.....do	12	.....do	Water pipe	10
3	.....do	12	.....do	.....do	11
4	.....do	12	.....do	Bonded rail	10
5	.....do	12	.....do	.....do	12
6	.....do	12	.....do	Water pipe	11

DETROIT, MICH.[a]

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
1	1-inch driven pipe	6	Sandy	Water pipe	11.8
2	.....do	6	.....do	.....do	10.1
3	.....do	6	.....do	.....do	6.3
4	.....do	6	.....do	.....do	6.3
5	.....do	6	.....do	.....do	8.1
6	.....do	6	.....do	.....do	14.8
7	.....do	6	Loam	.....do	14.6
8	.....do	6	.....do	.....do	3.9
9	.....do	6	.....do	.....do	11.4
10	.....do	6	Clay	.....do	9.0
11	.....do	6	.....do	.....do	10.9
12	.....do	6	.....do	.....do	13.3
13	.....do	6	.....do	.....do	10.3
14	.....do	6	.....do	.....do	18.5
15	.....do	6	.....do	.....do	17.9
16	.....do	6	Sand	.....do	8.0
17	.....do	6	.....do	.....do	17.4
18	.....do	6	.....do	.....do	47.5
19	.....do	6	.....do	.....do	68.1
20	.....do	6	.....do	.....do	7.9
21	.....do	6	Sand and clay	.....do	12.1
22	.....do	6	.....do	.....do	9.6
23	.....do	6	Sandy	.....do	7.1
24	.....do	6	.....do	.....do	12.9
25	.....do	6	.....do	.....do	29.9
26	.....do	6	.....do	.....do	12.7

[a] Measurements made by the Edison Illuminating Co., of Detroit.

TABLE 13.—Resistance of Ground Connections—Continued

CLEVELAND, OHIO

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
1	10 pounds. No. 4 copper wire in 15 pounds coke.	5	Clay	Water pipe	19
2	do	5	do	do	90
3	do	5	do	do	25
4	do	5	do	do	21
5	do	5	Clay over shale	do	49
6	do	5	do	do	28
7	do	5	do	Bonded rail	22
8	do	5	Rocky	Water pipe	250
9	do	5	Clay over rock	do	35
10	do	5	Wet sand	do	48
11	do	5	do	do	140
12	do	5	Sand	do	160
13	do	5	do	do	94
14	do	5	do	do	95
15	do	5	do	do	275
16	do	5	do	do	140

CANTON, OHIO

1	¾-inch driven pipe	15	Clay and gravel	Water pipe	40
2	do	15	do	do	85
3	do	15	do	do	90
4	do	15	do	do	180
5	do	15	Gravel	do	300
6	do	15	do	do	150
7	do	15	do	do	190

PITTSBURGH, PA.

1	¾-inch driven pipe	8	Sandy	Water pipe	63
2	do	8	Clay over shale	do	22
3	do	8	do	do	15
4	do	8	Clay	do	36
5	Two ¾-inch driven pipes 4 feet apart.	8	do	do	28
6	¾-inch driven pipe	8	Shale	do	32
7	do	8	do	do	36
8	do	8	Stony hillside	Bonded rail	80
9	do	8	Stony	Water pipe	190
10	do	8	do	Bonded rail	50
11	do	8	Filled ground	Water pipe	21

WASHINGTON, D. C.

1	Steel pole set in concrete	5	Clay and stones	3-point method	90
2	do	5	do	do	110
3	do	5	do	do	40
4	do	5	do	do	60
5	do	5	do	do	40

TABLE 13.—Resistance of Ground Connections—Continued

WASHINGTON, D. C.—Continued

Ground No.	Type	Depth	Soil	Auxiliary ground	Resistance
		Feet			Ohms
6	Steel pole set in concrete	5	Clay and stones	3-point method	80
7	.....do	5	Clay, low, in hollow	.....do	18
8	.....do	5	.....do	.....do	4
9	.....do	5	Clay	.....do	29
10	.....do	5	.....do	.....do	33
11	.....do	5	.....do	.....do	8
12	.....do	5	.....do	.....do	53
13	.....do	5	.....do	.....do	17
14	¾-inch driven pipe	10	Clay and stones	Water pipe	55
15	.....do	10	.....do	3-point method	25
16	.....do	10	.....do	Water pipe	61
17	.....do	10	.....do	.....do	50
18	.....do	10	.....do	.....do	24
19	.....do	10	.....do	Bonded rail	19
20	.....do	10	.....do	Water pipe	15
21	.....do	10	.....do	.....do	30
22	.....do	10	.....do	.....do	45
23	.....do	10	.....do	Bonded rail	26
24	.....do	10	.....do	Water pipe	39

1. METHOD OF MEASUREMENT

Nearly all of the measurements were made by the bridge method. At first it was thought desirable to transport ammeters and voltmeters to use where conditions were such that the bridge would not work, but it was soon found that occasion for their application would arise infrequently, and since they are somewhat cumbersome and liable to derangement from jolting in vehicles they were abandoned in favor of the bridge instrument, which is more compact and rugged.

No great difficulty was at any time experienced with the bridge method, although it was tried under nearly every condition that is likely to arise. That is, no serious difficulties were encountered that would not also have been encountered with the ammeter-voltmeter method. In fact, the bridge gave more or less satisfactory results in places where an ammeter and voltmeter could not readily have been used, or only with difficulty. For example, it was often found desirable to measure the resistance of lightning arrester grounds where there were no low-voltage circuits within reach from which current might be taken. Under these circumstances the ammeter-voltmeter method would require an independent source of current such as a hand generator, which would

be much heavier and more inconvenient to operate than the independent source of current already described for the bridge. As another example, it was sometimes found necessary to use a bonded street-car rail as an auxiliary ground connection. Here a variable difference of potential accompanying the return of direct current from the cars usually existed between the rail and the ground under test, and when the test circuit was closed, a fluctuating direct current was superimposed upon an alternating current with the result that a greater or less distortion of the current wave took place. With the bridge this distortion made no difference, a balance being easily obtained unless the hissing sound from the commutation of the direct current obscured the sound of the bridge current, or a sufficient direct current passed through the telephone receiver to draw down the diaphragm and hold it so the vibrations caused by the bridge current were inaudible; although the chances of this occurring were not found to be great, because of 50 measurements made in this way serious interference was met with in only three or four cases. And even in those, by taking advantage of periods when the cars were evidently standing still, or when the potential difference between track and ground was at its lower values, fair results were obtained. With ammeters and voltmeters, however, if special precautions are not taken the wave distortion just mentioned may give rise to errors in current and voltage readings, especially where grounds of low resistance are being tested. With alternating current at 110 or 220 volts, and grounds under test of high resistance, the chances of error are small in most cases, but the possibility of such errors should be kept in mind. The magnitude of the discrepancies which may arise can be estimated by connecting an ammeter between the rail and the ground under test. If the flow of direct current to ground is but a few per cent of the alternating current used its effects may be neglected.

2. PROCEDURE IN MAKING TESTS

The procedure followed in each place varied somewhat according to the records available, the character of the soil, and other factors. The main point observed was to select those ground connections of the different types in use which lent themselves most readily to making measurements. On this account lightning-arrester grounds were picked out wherever possible because they were in most cases separated from all electrical circuits by

spark gaps; and, since for this reason there was no leakage, no necessity existed for cutting the ground wire and splicing it again. In some places, however, where common grounds were used, or where lightning-arrester grounds were not plentiful enough, it was necessary to resort to tests upon low-voltage circuit grounds and if there was leakage, or more than one ground on each circuit, the ground wire had to be cut and reconnected, which added considerably to the labor and consumed a great deal of time.

An effort was everywhere made to make tests in all of the different kinds of soil, in high and low ground, and in places where extraordinary conditions existed, if any were known. The soils were classified roughly, no attempt being made to go beyond stating their general character. This was usually ascertained by looking at excavations or cut banks near by, and assuming that what was seen fairly represented the soil where the electrodes were buried.

With regard to the form of the electrode it was usually necessary to rely upon the memory of the person assigned by the utility to accompany the observer, as to depth and other characteristics, because in but few instances were records available which gave this information. Where a standard type had been adhered to no difficulty was experienced, but where the type had been changed a few times the kind of electrode was not always easy to determine, so the first column in Table 13 may in some instances be in error.

In the selection of auxiliary grounds water pipes were, of course, given preference. But if these were not near enough bonded street-car rails were taken next in order, and then grounded telephone messenger cables and other objects, such as driven well casings. Very little trouble was experienced in obtaining water pipes as auxiliary grounds within city limits. From such observations as were made in these territories it does not seem that more than 5 or 10 per cent of the area covered by the electrical systems was out of reach of fire plugs or service pipes. Being within reach, here means within 325 feet, as that was approximately the length of the wire used. As mentioned heretofore, very little trouble was experienced with high-resistance joints in service pipes or fire plugs, although a few were discovered. On numerous occasions high-resistance joints were suspected, but on checking the measurements by means of other service pipes, fire plugs, or bonded rails, it was usually found that the abnormally high resistance was in the ground connection itself.

In Table 13 the resistances given include the resistance of the leads and the auxiliary ground where the auxiliaries consisted of water pipes, bonded rails, or telephone messenger cables. Where other kinds were used the resistance was determined by the 3-point method if possible. In some cases, however, only one ground besides the one being tested was available, and here the resistance of the two series is given and the character of the auxiliary described in column 4. The resistance of the leads was 0.04 ohm per foot, and as it was not often that more than 100 feet of wire was used, and in practically every case where occasion arose to use more the resistance measured was rather high, no account was taken of it. Very few measurements were made where the leads made a difference of more than 1 or 2 per cent.

3. SUMMARY OF RESULTS

The results of the tests are summarized below under the following heads: (*a*) Resistances by kinds of soil; (*b*) resistances by types of grounds; and (*c*) average, minimum, and maximum resistances by cities. In addition, under (*d*), a brief description is given of the general practice followed in grounding by the different utilities.

(*a*) Resistances by Kinds of Soil.—The average, minimum, and maximum resistances according to kinds of soil are given in Table 14. The soils are grouped as they are in column 2 because it was found that electrodes embedded in clay, shale, adobe, gumbo, loam, and loam intermixed with a small amount of sand showed resistances covering about the same range of values. The minumum and maximum values were usually found under some extraordinary condition of dampness or dryness, respectively, and indicate no more than the wide variations due to differences in moisture content which may be anticipated in soils of the same nature as far as resistivity is concerned. It should be stated, however, that the differences in this case are due to local conditions rather than to widespread changes during the period the measurements are being made, such as would ensue from rainfall. For example, ground connections were found in soil wet with waste water of some kind, which gave very low resistances, whereas others were found in buildings where moisture apparently never entered, which gave very high resistances. With regard to rainfall, in about half of the places visited it was found that during the month preceding the date of making the measurements the pre-

cipitation had been above normal. In the rest it had been below, so the average resistances are about what they would ordinarily be for the autumn months, the time when the work was done. As indicated heretofore, the resistance for spring and autumn is about the average for the year, or midway between minimum and maximum.

TABLE 14.—Resistances by Kinds of Soil

Grounds tested	Soil	Average resistance	Minimum resistance	Maximum resistance
		Ohms	Ohms	Ohms
24	Fills, and ground containing more or less refuse such as ashes, cinders, and brine waste	14	3.5	41
205	Clay, shale, adobe, gumbo, loam, and slightly sandy loam with no stones or gravel	24	2.0	98
237	Clay, adobe, gumbo, and loam mixed with varying proportions of sand, gravel, and stones	93	6.0	800
72	Gravel, sand, or stones with little or no clay or loam	554	35	2700

The chief conclusion to be drawn from the results given in Table 14 is that unless a ground connection is made in soil containing little or no sand, gravel, or stones, its protective value is likely to be very small, and even where the ground conditions are of the best, to derive a degree of protection comparable with that obtained from the use of water pipes, requires 10 to 20 grounds in parallel on each low-voltage circuit. The greater the proportions of stones, gravel, and sand, the greater the resistances, and in places where there is almost no clay or loam of some form, but all gravel and stones, protection by grounds made with electrodes of limited extent is out of the question. The only way in which high voltages can be guarded against effectively in such places is to use water pipes or, with a lesser degree of effectiveness, a common ground wire.

(*b*) Resistances by Types of Grounds.—It will be noted from Table 13 that comparatively few electrodes of forms other than driven pipes were found, and for this reason it is not possible to make a satisfactory comparison. Moreover, to determine their relative merits requires that they be installed in reasonably uniform soil, whereas with few exceptions the ground connections tested were made in soil that was not only highly nonuniform, but of different kinds. The only place where electrodes of different forms were found in soil that would admit of comparison was in Omaha, Nebr., where tests were made on 16 Garton hydro-

grounds and 14 driven pipes, 1 inch in internal diameter, and 10 feet in length, all of which were embedded in yellow clay. The average resistance of the former was 28 ohms and of the latter 14 ohms. The hydrogrounds, therefore, appear to be much inferior to the pipes. In other places a small number of Paragon cones, Federal Cartridge Ground Plates, and Maxum Ground Boxes were tested, but nothing was discovered which would change the sense of the conclusion already given in this paper, viz, that at the same expense better results can be obtained with driven pipes than with these patented devices. The same thing was found to be true of plates and coils of wire, either with coke or without.

In addition to the tests just mentioned a few were made on steel poles. The resistance of steel poles is of interest because in some instances they are used as a means of grounding lightning arresters; in others they carry high-voltage circuits, the wires of which may come in contact with them and be the cause of current flow and a rise of potential difference between pole and ground, with consequent danger to linemen and others. All but four of the poles tested were situated in the District of Columbia, of which six were set 5 feet deep in clay and stones and surrounded with concrete. The average resistance of these was found to be 70 ohms, while the average resistance of driven pipes 0.75 inch in internal diameter and 10 feet in length in the same kind of soil was 35 ohms. The rest of the poles, seven in number, were set to the same depth in the same way in rather damp clay soil that appeared to be free from stones. The average of these was 23 ohms, or somewhat more than that of pipes of the size just mentioned in soil of the same kind. Besides the poles tested in the District of Columbia, tests were made on four poles in Paterson, N. J., which were set to a depth of 5 feet in very sandy soil and surrounded with concrete. These showed an average resistance of 205 ohms, which is about the same as the resistance of driven pipes in the same locality. Steel poles, therefore, do not compare unfavorably with pipes driven in the same kind of soil, but their resistance is high enough to make them dangerous if a high-voltage circuit becomes grounded to them, and they are hardly to be regarded as suitable for grounding lightning arresters or low-voltage circuits, unless a number of them are electrically connected [46] together. In this way, however, a fair grounding system

[46] See rule 305, National Electrical Safety Code.

can be provided; that is, by running say a galvanized stranded steel cable approximately equivalent in conductance to a No. 6 copper wire from pole to pole and bolting it fast. The length required may be estimated roughly by neglecting the resistance of the cable and assuming that the total resistance to ground varies inversely as the number of poles connected together. For instance, if the resistance per pole is 100 ohms the number required to give a resistance to ground of 2 ohms would be 50, which would require a length of cable of 1.2 miles with poles spaced 120 feet apart. If the resistance per pole were less the length required would be proportionately less.

(*c*) Average, Minimum, and Maximum Resistance by Cities.—In Table 15 are given the average, minimum, and maximum resistances measured in the different cities named in Table 13, and also an indication of the varieties of soil found in each place and the types of grounds upon which tests were made, or at least upon which most of them were made. In a number of places different types of grounds were found, but only the prevailing type is named. The soils ranged not only through all the varieties designated, but through mixture of them in different proportions as well. The minimum and maximum resistances, as stated heretofore, were usually found under extraordinary conditions as to soil or moisture content, or both. The minimum was in most cases encountered in some very damp place or in ground containing refuse; the maximum in some very dry place or in gravel or sand. These values, of course, are in nearly all instances exceptional, but at the same time they show the range of resistances that may be anticipated when making ground connections in soil of the different kinds encountered.

TABLE 15.—Resistances by Cities

No.	City	Soil	Type of ground	Average resistance	Minimum resistance	Maximum resistance
1	Newark, N. J.	Clay and marsh land	Driven pipes	[a] 10	2.5	800
2	Paterson, N. J.	Stony, clay, and sand over rock.	Pipes and steel poles.	340	20	700
3	Elizabeth, N. J.	Clay, shale, sand, and gravel.	Driven pipes	51	4.5	190
4	New York, Bronx district.	Clay, gravelly, stony	Standpipes [b]	17	6.0	45
5	Providence, R. I.	Gravel, sand, a little clay and loam.	Driven pipes	996	30.0	2700

[a] One abnormally high value omitted from this average. (See Table 11.)
[b] Three and four inch pipes running under curb to building.

TABLE 15.—Resistances by Cities—Continued

No.	City	Soil	Type of ground	Average resistance	Minimum resistance	Maximum resistance
6	New Haven, Conn	Gravel, sand, some clay	Driven pipes	23	15.0	920
7	Boston, Mass	Gravel, sand, clay	...do	548	7.0	2250
8	Philadelphia, Pa	Clay, marsh, stony	...do	133	5.8	1400
9	Scranton, Pa	Gravel, clay, stones	...do	162	19.0	490
10	Omaha, Nebr	Yellow clay	Driven pipes and hydrogrounds.	22	3.5	60
11	Denver, Colo	Clay, gravel, sand	Driven pipes	60	7.0	210
12	Colorado Springs, Colo	Sand, gravel, adobe	...do	92	13.0	350
13	Pueblo, Colo	Sand, adobe, stones	...do	35	3.5	210
14	Leadville, Colo	Stones, sand	Coils wire in coke	66	25.0	200
15	Salt Lake City, Utah	Gravel, sand, stones, and clay.	Driven pipes	61	5.5	210
16	Butte, Mont	Sand, gravel, stones, and clay.	Coils of wire	112	17.0	380
17	Helena, Mont	Sand, stones, clay	Driven pipes	90	21.0	205
18	Moorhead, Minn	Black loam over clay	Pipes and cones	28	7.0	90
19	Minneapolis, Minn	Gravel, sand, clay, stones	Driven pipes	114	7.0	490
20	Des Moines, Iowa	Clay	...do	11	6.0	28
21	Davenport, Iowa	Clay and loam	...do	11	5.5	25
22	Peoria, Ill	Gravel, sand, clay	...do	40	9.0	70
23	Chicago, Ill	Clay, sand	...do	19	7.0	43
24	Milwaukee, Wis	Clay, gravel, sand	...do	40	15.0	85
25	Indianapolis, Ind	Clay and gravel	...do	61	13.0	150
26	Cincinnati, Ohio	Sand, clay, stones	...do	39	11.0	200
27	Dayton, Ohio	Sand, gravel, clay, and stones.	...do	50	13.0	115
28	Toledo, Ohio	Clay	...do	10	8.0	12
29	Cleveland, Ohio	Clay, shale, stones, sand	Coils wire in coke	99	19.0	275
30	Canton, Ohio	Clay, gravel, sand	Driven pipes	133	40.0	300
31	Detroit, Mich	Clay, sand, loam	...do	15	3.9	68
32	Pittsburgh, Pa	Clay, shale, stones, sand	...do	43	15.0	190
33	Washington, D. C	Clay, stones	Pipes, steel poles	40	4.0	110

The data of greatest interest are those showing the average resistances. These averages were calculated without regard to the type of ground, and are simply the result of averaging all of the values obtained in each place. No account was taken of the type of ground because, in the first place, by far the greater part of the grounds tested were made with driven pipes of a limited range of sizes between which there is not a wide difference of resistance if driven in the same kind of soil, and, in the second place, those grounds tested which were made with electrodes other than pipes were few in number, and experiments made at the Bureau of Standards have shown that their resistances are not greatly different from those of pipes of the average length and size described in Table 13. Hence, little effect would be produced by making al-

lowances for the differences in size and shape of the electrodes; at least not enough to change any conclusions that might be drawn. The averages are, therefore, calculated from the results as they were obtained with no attempt at correction.

These averages show that in all but eight of the places named it is not practicable to make ground connections with single electrodes of limited extent having a resistance of less than 25 ohms each. In none of them is it possible to obtain a degree of protection comparable with that which can be had from water pipes except at an expense which in all but a few cases would be prohibitive. That is, the number of electrodes in parallel required to give a total resistance to ground of 0.25 ohm, the average resistance of water pipe grounds, would be so great that only in exceptional instances would it be practicable to install them. For example, in places where the average resistance of driven pipe grounds is 10 ohms, to obtain a resistance of 0.25 ohm would require 40 driven pipes in parallel; where the average resistance is 50 ohms the number of driven pipes would be 200, and so on. To install any such number of pipes on the average low voltage circuit is, of course, out of the question. The difficulty can be overcome to a greater or less extent by the use of a common ground wire, but even here the degree of protection afforded is not by any means equal to that of water pipes unless the common ground wire is itself connected to a water system and should be resorted to only where the latter are out of reach.

(*d*) General Practice in Grounding Secondary Circuits.—In the following cities water pipes are used, with driven pipes and other grounds installed, either as a measure supplementary to the use of water pipes or in places where the latter are not available: Newark, Paterson, Elizabeth, N. J.; New Haven, Conn.; Providence, R. I.; Boston, Mass.; Denver, Colo., and Canton, Ohio.

In Canton connection to the water system is made by running a wire down the pole and clamping it to the service pipe near the main. In all of the others connections to the pipes are usually made within the customer's premises. In New York City, Bronx district, a common ground wire is in use which is grounded to water pipes at all substations, and also to about 1500 "stand pipes" which contain service wires running under the curb to buildings. This common ground wire is formed by linking together the middle wires of all the low-voltage circuits which thus form a network over the whole secondary system.

In Butte, Mont., and Scranton, Pa., the type of ground most used is a coil consisting of about 10 turns of No. 4 wire stapled to the butt of the pole. In Leadville, Colo., and Cleveland, Ohio, coils of wire are also used, but instead of being stapled to the pole are embedded in about 15 pounds of coke at the foot of it. In all the other places visited driven pipes were used, with the exception of an occasional patented device, plate, local water system, or driven well casing. In Orange, Conn., near New Haven, a common ground wire has been installed consisting of a No. 6 copper wire run on top of poles, and connecting a large number of widely separated secondary circuits which are situated out of reach of water pipes and are grounded to driven pipes, local water systems, and well casings. Grounds are also placed at advantageous points along the line. The resistance, as determined by the bridge method, is less than 2 ohms, and it appears that the protection is next in degree, at least, to that afforded by water pipes.

There was a considerable variety in the methods of attaching wires to pipes, but the prevailing one seemed to be that of plugging the pipe about 4 inches below the top, inserting the wire, and pouring the pipe full of melted solder. This makes a very efficient and solid joint of good electrical conductance. Another method consisted in the use of "ground caps," which were made to fit over the top of the pipe with a longitudinal groove to receive the wire, and were driven on. In a few cases wires were attached by means of lugs which screwed on to the top of the pipe; in others by clamps, such as are commonly used for attaching ground wires to service pipes.

The use of molding to protect the ground wire from mechanical injury is not by any means universal. In many places no protection whatever is given, wire with weatherproof insulation being simply stapled to the pole. In other places, however, molding is erected which extends to the cross arm. The use of molding, or better yet, of insulating tubing, is especially to be recommended, both as a means of preventing breakage and, what is equally if not more important, as a means of protecting persons from electric shock. The possibility of breakage, of course, is not great, but it exists, especially in exposed places, and must be guarded against. Theft is another thing which must also be guarded against, and here molding may be of some assistance, especially against theft by small boys; but the best method of discouraging that practice is by the use of iron ground wires instead of copper. This reduces

the junk value of the material to such an extent that it is hardly worth while to carry it away, and yet the iron will serve as well as the copper and be stronger for the same conductance, but will not resist corrosion as successfully.

Not a few places were discovered in the course of the work where the practice existed of using a common ground for lightning arresters and secondary circuits. By far the greater number of the utilities consulted, however, disapproved of that practice. In two places where 3-phase, 4-wire 4000–2300 volt-distributing systems were used, the neutral wire was grounded at intervals, and this grounded neutral wire used in turn for grounding secondary circuits and lightning arresters. A low resistance to ground is provided in this way if the system is extensive, but there is a possibility of trouble in that the neutral wire may break, in which case, if a near-by secondary is grounded, as they usually are in this case, current at 2300 volts may flow to ground over the secondary circuit with the attendant possible dangers.

With regard to inspection, testing, and other matters pertaining to the practice of grounding, attention is directed toward Appendix I, which gives a summary of a large number of letters from electric utilities answering questions regarding their methods of protecting against high voltages.

In conclusion, the Bureau wishes to acknowledge the cordial cooperation and assistance of the following electrical utilities in obtaining the data compiled above:

Colorado.—Denver Gas & Electric Co., Denver; Colorado Springs Light, Heat & Power Co., Colorado Springs; Arkansas Valley Railway, Light & Power Co., Pueblo; The Colorado Power Co., Denver.

Connecticut.—The United Illuminating Co., New Haven.

District of Columbia.—Potomac Electric Power Co., Washington.

Illinois.—Central Illinois Light Co., Peoria; Commonwealth Edison Co., Chicago.

Indiana.—Merchants Heat & Light Co., Indianapolis.

Iowa.—Des Moines Electric Co., Des Moines; People's Light Co., Davenport.

Massachusetts.—The Edison Electric Illuminating Co., Boston.

Michigan.—The Detroit Edison Co., Detroit.

Minnesota.—Municipal Water & Light Plant, Moorhead; The Minneapolis General Electric Co., Minneapolis.

Montana.—Montana Power Co., Butte; Helena Light & Railway Co., Helena.

Nebraska.—Omaha Electric Light & Power Co., Omaha.

New Jersey.—Public Service Electric Co., Newark,

New York.—New York Edison Co., New York City.

Ohio.—The Union Gas & Electric Co., Cincinnati; The Dayton Power & Light Co., Dayton; Toledo Railway & Light Co., Toledo; Canton Electric Co., Canton; The Cleveland Electric Illuminating Co., Cleveland.

Pennsylvania.—The Philadelphia Electric Co., Philadelphia; Scranton Electric Co., Scranton; Duquesne Light Co., Pittsburgh.

Rhode Island.—Narragansett Electric Lighting Co., Providence.
Utah.—Utah Power & Light Co., Salt Lake City.
Wisconsin.—Milwaukee Light, Heat & Traction Co., Milwaukee.

XI. SUMMARY

The substance of this circular and the conclusions from it may be summarized as follows:

1. The resistance of a ground connection made with an electrode of limited extent depends directly upon the resistivity of the surrounding soil and also upon the form and arrangement of the electrode. The effect of the latter varies inversely as the electrostatic capacity in free space of the electrode and its image above the surface of the ground. The most advantageous form and arrangement are obtained when the electrostatic capacity is a maximum, since the latter enters as a factor in the denominator of the formula for the resistance of a ground connection. (See Appendix III.)

2. Contact resistance between clean metal and packed earth and also between rusty metal and packed earth is negligible as far as practical purposes are concerned. Where contact resistance of considerable magnitude exists it is in most cases due to paint, scale, or some impervious nonconducting material on the surface of the electrode.

3. Danger to life from electrical systems arises because of the occasional entrance of abnormally high voltages upon the low-voltage parts of electrical circuits and equipment, to which persons have access, through faults in insulation between high-voltage and low-voltage circuits. Such faults are developed for the most part by lightning and breakage of wires in storms, occasionally by high-voltage surges or deteriorated insulation.

4. The magnitude of the potential differences against ground which may appear upon low-voltage circuits or parts of equipment is governed by a number of factors, chiefly, however, by the voltage of the line with which contact is made and the relative location of the point of failure. For instance, with a 2200-volt distribution circuit feeding a low-voltage circuit through a step-down transformer a failure of insulation at an end turn of the high-voltage winding may raise the potential of the lighting circuit against ground to a value approaching 2200 volts unless provision is made for preventing it. A similar condition may arise with any low-voltage circuit if it makes contact with a high-voltage circuit.

5. Danger from high potentials between low-voltage circuits or parts of equipment and ground can best be averted by grounding the parts affected. For a high degree of safety to life the resistance of the ground connection should be such that with a current flow equal to the rated current of the nearest circuit breaker which will operate to disconnect the equipment or circuit concerned from the source of the dangerous voltage in the event of an accident to insulation, the potential difference between ground wire and ground will not exceed 150 volts, if the ground wire or circuit is accessible. Where both ground wires and circuits are inaccessible a higher voltage limit is permissible.

6. As a safety measure more adequate means should be provided for detecting accidental grounds on low-voltage circuits than is usually the case. The practice of cutting off protective grounds to avoid annoyance from accidental grounds and leaving them off indefinitely is hazardous, both to life and property, and should be discontinued. Where accidental grounds are discovered the party responsible for the operation of the circuit should be required to put it in safe working condition within a reasonable time.

7. The frames of all electrical machines that are connected, either directly or through transformers, to high-voltage lines should be grounded. Furthermore, for the reason that there is great uncertainty as to the maximum voltage that is not dangerous to life, it is desirable in all but one or two cases to ground the frames of machines operating upon lines of all voltages, unless it be those furnishing power at 150 volts or less in places where there are no inflammable nor explosive substances. An exception is where work must be done on brushes when they are alive. Here it may be well to insulate the frames at least while work is being done.

8. The frames of certain types of railway power-house switchboards should be insulated, or at least isolated, from ground, especially where earth return is used. The practice of grounding them to "fix" their potentials should be discontinued. For this amounts practically to connecting them to the negative bus bar, and severe accidents may occur when work is being done on live conductors at the back of the board through tools slipping and coming in contact with positive conductors and frame at the same time, unless spacings are great enough to prevent it or guards for live parts are provided.

9. For different classes of apparatus separate ground wires should be used, but more especially for those classes which have to do with protection against lightning. Moreover, if electrodes of limited extent are used, separate ground connections should also be provided, spaced not less than 6 feet apart. The reason for this is that if more than one class of apparatus is connected to the same ground wire a flow of current from one may cause a rise of potential against ground which is impressed upon all the rest. The greatest danger in this respect is to be expected from lightning arresters.

10. Water pipes offer by far the most desirable means of making ground connections, but where it is necessary to resort to other means, such as driven pipes or plates, an appreciable degree of protection can in some cases be obtained at reasonable expense. In a great many cases, however, grounds of the latter type will be found unsatisfactory. If a common ground wire is used a good degree of protection can be had, but the expense may be considerable, and the result not equal to that obtainable from water pipes, unless the common ground wire is connected to a water pipe.

11. There is no danger to water pipes of electrolysis by such stray alternating currents as may result from grounding low-voltage alternating-current circuits.

12. Low-voltage alternating-current circuits should be grounded at two or more points; from the standpoint of safety to life the more the better.

13. Ground connections for direct-current systems should be confined to one at the station.

14. Where it is allowable to ground a low-voltage circuit to pipes at more than one point, such grounding should be confined to a single pipe system, except where no electric railway with earth return is in operation, or there is no possibility of potential differences existing between metallically separate pipe systems. Moreover, there should be no insulating or other high-resistance joints between the points of connection to the pipe; for if there are the wires will act as a shunt to them and may thus carry a heavy flow of stray current from street railways, and in a measure nullify the effect of the joint.

15. Danger to employees of the water utility because of circuits being grounded to water pipes is practically nonexistent where multiple ground connections are used. Where there is a

single connection to a pipe, a remote possibility of danger exists, but this can readily be averted by requiring the electric company to disconnect the wire before work is begun on the pipes and to reconnect it after the work is done.

16. The resistance of ground connections made with electrodes of limited extent may vary with seasons to the extent of several hundred per cent. These changes are caused by changes in the temperature and moisture content of the soil.

17. The resistance of water-pipe ground connections varies but slightly with the seasons. This is due to the fact that a large part of the total resistance of such ground connections is contributed by the joints of the pipe itself, which are of relatively constant resistance, while only a small part of the total resistance is contributed by the soil, which is extremely variable. Changes in the moisture content and temperature of soil, therefore, produce but slight changes in the total resistance of water-pipe ground connections.

18. The resistance of ground connections made with electrodes of limited extent may be greatly decreased by salting, or dissolving any substance in the soil water surrounding the electrode which decreases its resistivity.

19. Ground connections can dissipate energy at a limited rate. This rate depends upon the moisture content of the soil, the rate at which moisture will travel by capillary action and the distance which it will cover, the size of the electrode, and other factors. If it is exceeded, drying of the soil will occur with a great increase of resistance. A pipe driven to a depth of 10 feet in moist, moderately salted earth may be estimated as having capacity to dissipate energy at a rate from 5 to 20 kw without an increase of resistance.

20. When current flows through a ground connection a potential gradient exists in the surrounding surface of the ground. For electrodes of limited extent, such as driven pipes and plates, its value varies roughly as the inverse square of the distance from the electrode, and directly as the current in amperes. There is not much danger to persons from the resulting potential differences if the safety requirements in regard to resistance are complied with unless it be that between ground wire and ground; but danger from this can readily be averted by covering the ground wire with insulating material. There is, however, some danger to animals from the potential differences in the ground, and much

trouble can be avoided by keeping such trespassers away from ground connections by fencing or by other means.

21. Substantial construction is one of the first considerations in making ground connections and should never be sacrificed to expediency. Unless workmanship and materials are of the best the protection afforded may be inadequate and unreliable.

22. It is desirable to maintain at all times the continuity of the connection to ground. Ground wires should, therefore, be carefully protected from mechanical injury. In line with this, ground connections to water-service pipes should be made at the point where there is the least likelihood of the pipe being disconnected between the point of attachment of the ground wire and the main. If the water meter is between the ground wire and the main a jumper of the same size as the ground wire should be put around it. If a ground wire needs to be disconnected this should be done by the electric-service company, and subsequently be reconnected by it.

23. The general practice in regard to circuit ground wires is to use No. 6 copper as a minimum size. Experience indicates that this is of sufficient mechanical strength. The current-carrying capacity required of a ground wire or of several in parallel is determined by the current rating of the nearest cut-out which will operate to break the circuit in the event of an accident to insulation.

24. Ground connections should be inspected at intervals not exceeding a year. Even shorter intervals are preferable. In no case should inspection be omitted, for it is unsafe to leave a ground connection without attention.

25. When a ground connection is installed its resistance should be measured. Reasonable assurance should also be had that it will carry the maximum current likely to flow through it without drying the soil and causing an increase of resistance. Subsequent tests may be confined to resistance measurements, say once in four years on driven pipes, once in two years on plates, and once in every year on salted ground connections.

26. For making resistance measurements the ammeter-voltmeter method with alternating current is the most accurate, but is in many cases inconvenient for field work. Where alternating current is not available from service lines, good results may be obtained with direct current, or with a Kohlrausch bridge, using an easily portable source of alternating or oscillating current.

Testing with lamp banks or fuses should be confined to ascertaining whether ground wires are continuous, and to similar purposes. Testing with magnetos should be abandoned, and testing with a voltmeter should not be relied upon for more than a bare indication of the condition of a ground connection.

27. Experience has not shown that grounding newly installed low-voltage circuits increases the fire hazard from them, nor has it shown that the interference with service caused by grounding is a factor that needs seriously to be reckoned with. On the contrary, the safety secured to life and property from high voltage appears to be all clear gain. In grounding old work the hazard is not increased unless the insulation on the ungrounded wires is very weak, and is decreased if the insulation has failed to a sufficient extent to blow fuses and reveal the trouble at the time the ground connections are made.

28. On account of the danger of fires or explosions, gas pipes should not be used for grounding except in special instances where the possibility of even slight current flow is negligible. Moreover, the almost invariable presence of water pipes makes connection to gas pipes unnecessary.

29. Because of the great advantage to the public, and the slight disadvantage, if any, to the public-service corporations resulting from grounding to water pipes, such grounding should be made compulsory in cases where it is necessary to protect human life. There is, moreover, a joint responsibility between the several public-service companies concerned, because both contribute to the life hazard by running their pipes and circuits near each other within buildings.

30. One hundred and seven of the 418 companies communicated with in the course of this investigation place the cost of making ground connections from \$2 to \$5. Other sources of information place the cost from \$5 to \$15. The available data on costs, however, are insufficient to enable a dependable estimate to be made.

31. Specifications for ground connections should be based upon the results which it is necessary to produce, rather than upon arbitrary methods of construction, as has been the custom to a large extent in the past.

32. Measurement of the resistance of ground connections made with driven pipes and other forms of electrodes of limited extent as now used in different parts of the country show that it is difficult thus to obtain adequate protection from high voltages even where

soil conditions are the most favorable. And where conditions are unfavorable, as where there is a great deal of gravel and sand, adequate protection is ordinarily not obtainable except by the use of water pipes, or a common ground wire. The latter, however, is subject to breakage the same as a line wire, which may destroy the protection; and at the same time, even where there is no danger of breakage, the degree of safety is not as great as that afforded by water pipes.

WASHINGTON, October 3, 1917.

30263°—18——14

APPENDIXES

Appendix I.—SUMMARY OF CORRESPONDENCE WITH ELECTRIC COMPANIES ON GROUNDING

Below is given a brief summary of answers to questions addressed to a large number of electric-service companies in the United States on grounding. The results of this correspondence are given here as indicating the present status of the practice of grounding to avert dangers from electrical systems. They show that although earthing is quite general, many operators are not convinced of its efficacy as a preventive of accidents to life and property, and also that as it is now practiced it is in many cases of questionable worth as a measure of safety.

Total number of electric-service companies from which replies were received	418
Q. 1. Do you believe grounding desirable?	
Yes	271
No	62
Doubtful	14
Conditional	29
No replies	42
Q. 2a. What percentage of low-voltage direct-current circuits do you ground?	
One hundred per cent	66
Less than 100 per cent	9
None	118
At station only	3
Having railway circuits only	2
Mine work only	1
No direct-current circuits	157
No replies	62
Q. 2b. When did you begin?	
1915	5
1914	5
1910–1913	14
Prior to 1910	24
Prior to 1900	11
No direct-current circuits	157
No replies	202
Q. 3a. What percentage of 110–220 volt circuits do you ground?	
One hundred per cent	199
Fifty per cent or more	18
Less than 50 per cent	31
Q. 3a—Continued.	
None	128
All new installations	3
All large transformers	1
No alternating-current circuits	1
No replies	37
Q. 3b. When did you begin?	
1915	16
1914	38
1910–1913	99
Prior to 1910	64
Prior to 1900	4
No alternating-current circuits	1
No replies	196
Q. 4a. What percentage of 110–220–440 2 or 3 phase circuits do you ground?	
One hundred per cent	85
Fifty per cent or more	6
Less than 50 per cent	6
One hundred per cent of 110–220 volt circuits	22
Twenty-five per cent of 110–220 volt circuits	1
Four hundred and forty volt circuits	2
No 2 or 3 phase circuits	213
Neutrals of all transformers	1
Conditional	1
No 2 or 3 phase circuits grounded	15
No replies	67
Q. 4b. When did you begin?	
1915	8
1914	18
1910–1913	52

Q. 4b—Continued.

Prior to 1910	23
Prior to 1900	2
No 2 or 3 phase circuits	15
No replies	300

Q. 4c. In your experience and belief is this a good practice?

Yes	175
No	66
Doubtful	13
Conditional	11
No replies	153

Q. 5. How frequently do you make grounds on each secondary?

Each transformer	109
Transformer and also at services	10
Each service	24
Transformer and at intervals of 250 to 1000 feet of line	8
Irregularly, 250 to 1000 feet	71
More than 1000 feet apart	4
In manholes	2
Common ground wire	2
No replies	188

Q. 6a. How often do you inspect grounds?

Intervals of 2 to 5 years	3
Intervals of 1 to 2 years	5
Intervals of 1 year	81
Intervals of 6 months or less	43
No systematic inspection	59
No inspection of any kind	12
No replies	215

Q. 6b. How often do you test them?

Intervals of 2 to 5 years	3
Intervals of 1 to 2 years	1
Intervals of 1 year	31
Intervals of 6 months or less	18
Not systematic	35
None of any kind	47
Answering "yes," without stating interval	23
No replies	260

Q. 7. Is grounding required by ordinance in your city?

Yes	29
No	302
Required by State law	3
No replies	84

Q. 8. Do you ground at poles or within buildings, or both?

At poles	165
In buildings	33
Both	65
Manholes	3
Common ground wire	2
No replies	151

Q. 9a. In how many cases have you found that grounding protects from primary or other crosses?

Yes	2
One to three	30
Three to ten	11
More than 10	4
Several	14
Many	15
All	5
No record or no crosses	79
No replies	258

Q. 9b. Have persons been injured or killed on your grounded circuits?

Yes	20
No	231
No replies	167

Q. 9c. Have fires resulted from grounding?

Yes	14
No	222
No replies	182

Q. 10a. Do you ground on water or gas systems or both?

Water	115
Gas	2
Both	24
Neither	99
No replies	178

Q. 10b. Do you use other types of ground? If so, what?

No	4
Driven pipes	123
Buried plates	33
Driven rods	37
Cones, or cones and pipes, rods or rails	20
Pipes and plates	19
Pipes and rail	7
No replies	175

Q. 11. Does the water company or water department object to grounds on its system?

Yes	48
No	196
Ordinance against it	3
Not known	10
No replies	161

Q. 12. What is your average expense for making a ground?

Between $1 and $2	59
Between $2 and $5	107
Between $5 and $10	23
More than $10	5
No replies	224

Q. 13. What is your average expense for maintaining a ground?

Between 10 and 25 cents	10
Between 25 cents and $1	17
Between $1 and $3	1
Between $3 and $5	1
No replies	389

Q. 14. How deep do you place grounds other than those on piping systems?

Between 3 and 6 feet deep	83
Between 6 and 10 feet deep	104
Between 10 and 20 feet deep	44
More than 20 feet deep	3
No replies	184

Q. 15a. For what length of time do you find your average ground continues suitable?

From 2 to 4 years	11
From 4 to 8 years	9
From 8 to 12 years	12
More than 12 years	2
No replies	384

Q. 15b. For what current do you find your average ground suitable?

Five to 20 amperes	14
Twenty to 50 amperes	8
Fifty to 100 amperes	10
Capacity of wire	1
No replies	385

Q. 16a. What electrical resistance do you obtain on your grounds?

Less than 1 ohm	5
One to 5 ohms	4
Five to 20 ohms	15
Twenty to 50 ohms	5
More than 50 ohms	5
No replies	384

Q. 16b. This resistance is based on what current passing and for what length of time?

One to 5 amperes	9
Five to 10 amperes	4
Ten to 30 amperes	7
No replies	398

Q. 17a. What increase of resistance do you find on grounds after one year?

No increase	9
Slight increase	2
Fifty per cent increase	1
Decrease	2
No replies	404

Q. 17b. After five years?

Very little	1
None	5
No replies	412

Q. 18. What current-carrying capacity do you provide for your grounds?

Twenty to 50 amperes	18
Fifty to 100 amperes	48
One hundred to 500 amperes	5
Capacity of transformer	1
Same as line	4
No replies	342

Q. 19. How much are you bothered with electrolysis from earth currents in your ground connections?

None	179
Slight	16
Some	4
No replies	219

Q. 20. What size of ground wires do you use?

No. 14	1
No. 8	3
No. 6	130

Q. 20—Continued.

No. 4	59
No. 3	1
No. 2	3
No. 00	4
No. 0000	1
No. 6 to 3/0	1
No. 6 to No. 4	27
No. 2 to No. 6	2
No. 4 to No. 8	1
No. 6 to No. 00	1
No. 6 to No. 0	3
No. 2 to No. 4–No. 6	3
No. 2 to No. 4	1
No. 6 to No. 8	2
No. 8 to No. 0	1
No. 4 to 500 000 cm	2
No. 6 to 0000	3
No. 4 to No. 10	1
No. 1 to No. 4	1
No. 9 Fe	1

Q. 20—Continued.

Seven-strand iron cable	1
Five-sixteenths inch iron	1
No. 6 BB	2
Capacity of transformer	1
Same as secondary	5
Same as line	2
Same as neutral wire	1
No replies	152

Q. 21. Do you approve of grounding low-voltage circuits to conduit containing wires in buildings, utilizing the conduit ground wire as the ground for the circuit?

Yes	55
No	145
Conditional	14
Doubtful	4
No replies	200

Appendix II.—RULES COVERING METHODS OF PROTECTIVE GROUNDING OF CIRCUITS, EQUIPMENT AND LIGHTNING ARRESTERS FOR STATIONS, LINES, AND UTILIZATION EQUIPMENT, BEING SECTION 9 OF THE NATIONAL ELECTRICAL SAFETY CODE

Contents

90. Scope of the Rules

The following rules apply to all lightning arrester grounding and to the grounding of all circuits, equipment, or wire runways, when the grounding is intended to be a permanent and effective protective measure. These rules do not require that grounding shall be done, but cover the methods for protective grounding. The rules requiring grounding, in accordance with the methods specified below, are included under parts 1, 2, 3, and 4 of the National Electrical Safety Code.

Other methods of construction and installation than those specified in the rules may be used as experiments to obtain information, if done where supervision can be given by the proper administrative authority.

The following rules do not apply to the grounding of arresters on signal circuits to the grounded return of trolley or third-rail systems, nor to the grounding of lightning protection wires where these are not connected to electrical circuits or equipment.

91. Application of the Rules and Exemptions

(*a*) The rules are intended to apply to all such installations, except as modified or waived by the proper administrative authority or its authorized agents, and are intended to be so modified or waived in particular cases whenever any rules are shown to involve expense not justified by the protection secured, or for any other reason to be impracticable, or whenever it is shown that equivalent or safer construction can be more readily provided in other ways.

(*b*) The intent of the rules will be realized (1) by applying the rules in full to all new installations, reconstructions, and extensions, except where any rule is shown to be impracticable for special reasons, or where the advantage of uniformity with existing construction is greater than the advantage of construction in compliance with the rules; (2) by placing grounds on existing installations or bringing present grounds into compliance with the rules, except where the expense involved is not justifiable.

The time allowed for bringing existing installations into compliance with the rules will be determined by the proper administrative authority.

(*c*) It will sometimes be necessary to modify or waive certain of the rules in case of temporary installations or installations which are shortly to be dismantled or reconstructed.

(*d*) In cases of emergency or pending decision of the administrator the person responsible for the installation may decide as to modification or waiver of any rule, subject to review by proper authority.

92. Where Ground Conductor Shall be Attached (When Grounding is Required by this Code, or is Installed as a Protective Measure, See Rule 304)

(*a*) Direct-Current Distribution Systems.—The neutral of three-wire direct-current systems shall be grounded at one or more supply stations, but not at individual services nor within buildings served. One side of a two-wire direct-current system may be grounded, but at one station only.

In three-wire systems the neutrals entering any junction box should be bonded together, but the box should not be specially grounded.

In two-wire systems the grounded side of the circuit should be insulated from ground except at the station ground connection.

(*b*) Alternating-Current Distribution Systems.—All secondary distribution systems shall be grounded at the building services or near the transformer (or transformers) either by direct ground connection (through water-piping system or artificial ground, see rule 94) or by the use of a system ground wire to which are connected the grounded conductors of many secondary mains and which is itself effectually grounded at intervals that will fulfill, for any secondary utilizing the system ground wire, the resistance and current-carrying requirements of rule 96a.

Single-phase, three-wire distribution systems shall be grounded at the neutral conductor. Two-wire, single-phase systems shall be grounded at the neutral point or on either conductor. Two-wire, single-phase and two or three phase systems shall, in general, be grounded at that point of the system which brings about the lowest voltage from ground of unguarded current-carrying parts of connected devices and also permits most convenient grounding.

Where any phase of a two or three phase system is used for lighting, that phase should be grounded and at the neutral conductor, if one is used.

In the absence of direct grounds at all building services, ground connections shall be made to the grounded neutral or other grounded conductor of a secondary system supplying more than one utilization equipment at intervals that will fulfill the resistance and current-carrying requirements of rule 96a.

Where the secondaries of transformers are supplying a common set of mains the fuses shall be installed only at such points as will not cause the loss of the ground connections after the fuses in the transformer circuits or mains have been blown.

Multiple grounds are preferable in all cases, because of the assurance provided against loss of the protection afforded by the chance disconnection of any ground connection.

Grounds other than the single-ground connection at the building service shall not be made to alternating-current secondaries within the buildings served.

(*c*) Lightning Arresters.—The connection to a lightning arrester shall be at such a point that its ground conductor is as short and straight as practicable.

Ground conductors for lightning arresters should not pass through iron or steel conduits unless electrically connected to both ends of such conduits.

(*d*) Equipment and Wire Runways.—The point at which the ground conductor is attached to equipment or wire runways shall, if practicable, be readily accessible.

93. Ground Conductor

(*a*) Material and Continuity.—The ground conductor shall be of copper or of other metal which will not corrode excessively under the existing conditions and, if practicable, should be continuous. Joints shall be so made and maintained as to conform to the resistance and current-carrying capacity requirements of rule 96.

Ground connections from circuits should not be made to jointed piping within buildings, except that water piping outside of meters and beyond any point which is liable to disconnection may be used. (See rules 94*a*, 95*a*, and 95*b*.)

No automatic cut-out shall be inserted in the ground conductor or connection except in a ground connection from equipment where its operation will immediately result in the automatic disconnection from all sources of energy of the equipment so grounded; no switch shall be so inserted except in plain sight, provided with distinctive marking and effectively isolated from unqualified persons. (See also rule 92*b*, par. 4.)

(*b*) Size and Number.—For grounding circuits the ground conductors shall have a combined cross section (and current capacity) sufficient to insure the continuity of the ground connection and its continued compliance with rule 96*a*, under conditions of excess current caused by accidental grounding of any normally ungrounded conductor of the circuit. No individual ground conductor for electrical circuits shall have less current capacity than that of a No. 6 copper wire, except that for additional grounds after the first on any circuit, smaller ground wires may be used, provided that they are in no case smaller than the conductor to which they are attached nor smaller than No. 10 copper.

For lightning-arrester ground connections the ground conductor or conductors shall have a current-carrying capacity sufficient to insure continuity of the ground connection under conditions of excess current caused by or following discharge of the arrester. No individual ground conductor shall be smaller than a No. 6 wire.

For electrical equipment the current-carrying capacity of a ground conductor shall be not less than that provided by a copper wire of the size indicated in the following table. When there is no cut-out protecting the equipment, the size of ground conductor will be determined by the design and operating conditions of the circuit.

Capacity of nearest automatic cut-outs:	Required size ground conductor American Wire Gauge
200 to 500 amperes	4
100 to 200 amperes	6
30 to 100 amperes	10
10 to 30 amperes	14

In portable cord to portable equipment protected by fuses not greater than 10-ampere capacity, a No. 18 ground wire may be used.

(*c*) Mechanical Protection and Guarding Against Contact.—Where exposed to mechanical injury the ground conductor shall be protected by substantial conduit or other guard. Guards for lightning-arrester ground conductors should be of non-magnetic material unless the ground conductor is electrically connected to both ends of the guard.

If the resistance of the ground connection is in excess of the values in rule 96 for water-pipe grounds, the ground conductor except in rural districts shall be protected

and guarded by being inclosed in insulating conduit or molding to protect persons from injury by coming into contact with it.

Such a high resistance may exist where artificial grounds are necessarily permitted in lieu of the preferable grounds to buried metallic water-piping systems.

Mechanical protection and insulating guards should extend for a distance of not less than 8 feet above any ground, platform, or floor from which ground conductors are accessible to the public. (See also rule 246.)

Insulating mechanical protection is advisable for single-arrester grounds, even when the connection is made to a water-piping system, and has therefore a low resistance, since a single connection is liable to be accidentally broken.

Even where ground connections have a resistance not exceeding that specified in rule 96 and no guard is therefore provided (or as an additional protection to persons even where guards are used) artificial grounds may be arranged to minimize the potential gradient along the surface of the earth by use of radial connecting wires underneath the earth surface or by other suitable means.

A circuit ground conductor shall be guarded as required for current-carrying conductors of the circuit, unless the ground conductor is entirely outside buildings, has strength and current capacity not less than that of No. 6 copper wire, and the circuit is elsewhere grounded by other ground conductors, except that in stations substantial bare ground busses may be used.

(*d*) Underground.—Wires used for ground conductors, if laid underground, shall, unless otherwise mechanically protected, be laid slack to prevent their being readily broken, and shall have joints carefully painted or otherwise protected against corrosion.

94. Nature of Ground Connection.

The ground connection shall be permanent and effective and be made as indicated in (*a*), (*b*), or (*d*) below; always as in (*a*), if (*a*) is available (except as per rule 97*b*).

(*a*) Piping Systems.—For circuits, equipment, and arresters at supply stations, connections shall be made to all available active continuous metallic underground water-piping systems between which no appreciable difference of potential normally exists, and to one such systems if appreciable differences of potential do exist between them. At other places connections shall be made to at least one such system, if available. Gas piping should not be used. (See rules 93*a*, 95*a*, and 95*b*.)

"Available" in this rule means ordinarily within 500 feet for stations.

The protective grounding of electrical circuits and equipment to water-pipe systems in accordance with these rules should always be permitted, since such grounding offers the most efficient protection to life and property and is not injurious to the piping systems.

(*b*) Alternate Methods.—Where underground metallic piping systems are not available, other methods which will secure the desired permanence and conductance may be permitted. In many cases metal well casings, local metal drain pipes, and similar buried metal structures of considerable extent will be available and may be used in lieu of extended buried water-piping systems.

In some cases ground connection may be made to the steel frame of a building containing the grounded circuits or equipment, to which frames of machines and other noncurrent-carrying surfaces should also then be connected. In such cases the building frame should be itself well grounded by effective connection to the ground. This may require artificial grounding for steel frame buildings supported on masonry or concrete (unreinforced) footings.

(*c*) Artificial Grounds.—When resort must be had to artificial grounds, their number should be determined by the following requirements:

1. Not more than one such ground is required for lightning arresters, except when for large current capacity. At least two grounds are required for low-voltage alternating-current distribution circuits at transformers or elsewhere.

2. Where no part of the circuit or equipment protected can be reached by persons while they are standing on the ground or damp floors, or by persons while touching any metallic piping to which the ground wire is not effectively connected a single artificial ground may be used even if its resistance exceeds that specified in

rule 96. In such cases it is desirable to provide guards for the ground conductor in accordance with rule 93*c* wherever it is otherwise accessible, or to provide insulating mats or platforms so located that persons can not readily touch the ground conductor without standing on such mats or platforms.

(*d*) GROUNDS TO RAILWAY RETURNS.—Protective ground connections should not be made to railway negative return circuits when other effective means of grounding are available, except ground connections from electric railway lightning arresters.

When ground connections are of necessity made to the grounded track return of electric railways, they shall be made in such a manner as not to afford a metallic connection (as indirectly through a grounded neutral with multiple grounds) between the railway return and other grounded conducting bodies (such as buried piping and cable sheaths).

This rule does not prohibit the making of drainage connections (which are not protective grounds) between piping systems and railway negative return circuits for the prevention of electrolysis.

Multiple protective ground connections from other circuits to railway returns should be avoided, and where multiple artificial grounds are made on such other circuits near such railway returns, they should be so arranged as to prevent the flow of any considerable current in and between such connections, thus reducing their effectiveness or causing other damage.

95. Method.

(*a*) Ground connections to metallic piping systems should be made (except as permitted in *b*) on the street side of water meters, which might interrupt the continuity of the underground metallic pipe systems, but connections may be made immediately inside building walls to secure accessibility for inspection and test. When water meters are located outside buildings or in concrete pits within buildings where piping connections are imbedded in concrete flooring, the ground connection may be made on the building side of the meters, if they are suitably shunted.

(*b*) When the making of a ground to a piping system outside meter or other device would involve a long run, connection for equipment or wire runways (but not for circuits) may be made to the water-piping system at a point near the part to be protected, provided there are no insulating joints in the pipe to prevent a good ground. In such cases care should be taken to electrically connect all parts of the piping system liable to create a hazard (if they become alive) and to shunt the pipe system where necessary around meters, etc., in order to keep the connection with the underground piping system continuous.

Gas-piping systems within buildings should not be used for purposes of this rule, except that gas piping need not be insulated from otherwise well-grounded electrical fixtures and where the making of another ground connection for a fixture would involve a long run and the fixture is therefore, of course, not within reach of plumbing or plumbing fixtures, the gas piping may for small fixtures be utilized as the sole ground connection. Where so used the gas-piping and water-piping systems within the building shall be grounded at their points of entrance. (See rule 93*a* and 94*a*.)

(*c*) The ground connection to metallic piping systems should be made by sweating the ground wire into a lug attached to an approved clamp and firmly bolting the clamp to the pipe, after all rust and scale have been removed, or by soldering the ground connection into a brass plug which has been tightly screwed into a pipe fitting, or, where the pipe is of sufficient thickness, screwed into a hole in the pipe itself, or connection may be made by other equivalent means. The point of connection should be as readily accessible as possible, and the position should be recorded.

With bell and spigot joint pipe it may be necessary to connect to several lengths where circuits or equipment of large current-carrying capacity are being grounded.

(*d*) Artificial grounds should be located where practicable below permanent moisture level, or failing this at least 6 feet deep. Each ground should present not less than 2 square feet surface to the soil. Areas where ground water level is close to the surface should be used when available.

96. Ground Resistance.

(*a*) Limits.—It is recommended that the combined resistance of the ground wires and connections of any grounded circuit, equipment, or lightning arrester should not exceed the values given below, if ground connections made according to rule 94 will sufficiently limit the resistance.

It will frequently be impracticable with artificial grounds to obtain resistances in dry or other high resistance soils as low as the values given below for ordinary soils. In such cases use two grounds as defined in rule 95*d*, and no requirement will be made as to resistance. (See also rule 94*c*–2.)

The current stated opposite the different resistances in the table is either the current capacity of a circuit from which leakage can occur to the grounded circuit, or the continuous current capacity to which the grounded equipment or arrester is limited by design or by automatic cut-outs.

Where a secondary is exposed only through transformer windings, this current capacity will be that of the primary fuse of the transformer. Where the secondary is exposed by the conductors of conflicting or crossing high voltage circuits, the current capacities will be those of the automatic cut-outs in such circuits.

Amperes	Water-pipe grounds	Artificial grounds, ordinary soils
	Ohms	*Ohms*
Less than 10	15	25
Ten to 25	6	25
Twenty-five and above	3 or less	25

The product of the corresponding numbers in the first and second columns is never greater than 150 volts—that is, the potential difference due to the stated current is never greater than 150 volts—where connections are made to water pipes.

Where more than one ground is made on the same circuit, equipment, or arrester in the same vicinity, all such grounds are considered collectively in respect to meeting the requirements of this rule.

(*b*) Checking.—The resistance of station grounds should be checked when made. With artificial grounds this check may be made by measuring the voltage between the grounded point of the circuit, or the grounded frame of the equipment or the grounded point of the lightning arrester and an auxiliary metal reference rod or pipe driven into the ground, while a measured current is flowing through the ground connection and any exposed metal piping or other artificial ground in the vicinity, but not within 20 feet.

If the station ground is to water piping, the check may be made with current flowing through the water piping and some independent piping system or artificial ground in the vicinity, but not within 20 feet.

The auxiliary rod or pipe should be at least 10 feet from any artificial ground or piping systems through which the measured current is made to flow.

All ground connections shall be inspected periodically.

Ground connections on distribution circuits should, when installed, be tested for resistance unless multiple grounding to water-piping systems is used.

97. Joint Use of Grounds and Ground Conductors for Different Systems.

(*a*) Ground Conductors.—Ground conductors should be run separately to the ground (or to a sufficiently heavy grounding bus or system ground cable which is well

connected to ground at more than one place) from equipment and circuits of each of the following classes:

1. Lightning arresters.
2. Secondaries connected to low-voltage lighting or power circuits.
3. Secondaries of current and potential transformers and cases of instruments on these secondaries.
4. Frames of direct-current railway equipment and of equipment operating in excess of 750 volts.
5. Frames of utilization equipment or wire runways other than covered by item 4.

(*b*) Grounds.—Lightning-arrester ground connections shall not be made to the same artificial ground (driven pipes or buried plates) as circuits or equipment, but should be well spaced and, where practicable, at least 20 feet from other artificial grounds.

Appendix III.—DERIVATION OF FORMULA FOR THE RESISTANCE OF A GROUND CONNECTION

Let (1) and (2), Fig. 38, be two metallic bodies embedded at a distance from each other in an infinitely extended semiconducting medium like the earth. Let it be supposed that body (1) is continuously maintained at a potential $+V_1$ and body (2) at a potential $-V_2$. The difference of potential between (1) and (2) will be $V=V_1+V_2$. A current I will flow from (1) to (2) through the medium, which offers a resistance R. Accompanying the difference of potential V between (1) and (2) there will be an electric intensity E at all points in the medium, which will correspond to a charge of static electricity $+Q$ on body (1) and $-Q$ on (2). Suppose a closed surface S of any form to be drawn about (1) but not including (2).

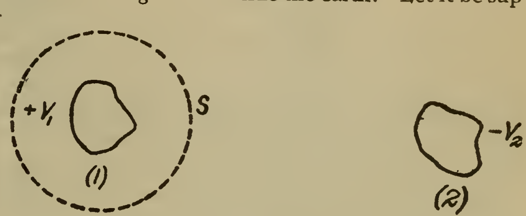

Fig. 38

Let $d\,s$ be an element of area of this surface,
n, the direction normal to the surface,
E_n, the normal component of the electric intensity at any point on the surface,
i_n, the normal component of the current density at any point on the surface,
K, the dielectric constant of the medium, and
ρ, its resistivity.

By Gauss's theorem $\int\int E_n ds = \frac{4\pi}{K} Q$. Also $-\frac{\delta V}{\delta n} = E_n$.

By Ohm's law $-\frac{\delta V}{\delta n} dn = i_n ds \bullet \rho \frac{dn}{ds} = E_n dn$, or

$\rho i_n ds = E_n ds$. Integrating $\rho \int\int i_n ds = \int\int E_n ds$.

$$\therefore \rho I = \frac{4\pi}{K} Q. \qquad (a)$$

Now $Q = C_1 V$, where $\frac{K}{C_1}$ is the electrostatic capacity between bodies (1) and (2), and by Ohm's law, $I = V/R$.

Substituting for I and Q in equation (a), therefore,

$\rho=\frac{4\pi}{K} C_1R=4\pi CR$, where C is the electrostatic capacity between (1) and (2) in medium of dielectric constant equal to unity, supposing the relative positions of the bodies to be the same.

Hence, the resistance $R=\rho/4\pi C$.

It is obvious that this formula applies to either two bodies or one; that is, either to a case where current flows from one body to another, or to a case where current flows from a single body toward infinity; depending upon whether C is calculated for the condenser formed by the two oppositely charged bodies or for a single body in free space. To clear up this last statement it is only necessary to consider that (2) is a shell inclosing (1) and infinitely large. In this case V_2 becomes equal to zero, $V_1=V$, and the electrostatic capacity C becomes that of (1) in free space; consequently R is made to refer to (1) only, and the current I is supposed to flow away from (1) toward infinity. It is also evident that it is immaterial whether body (1) is a single conductor or several separate conductors, as long as the surface S incloses all of them, except that in calculating C and R all of the electrodes inclosed by the surface S should be treated as a single electrode.

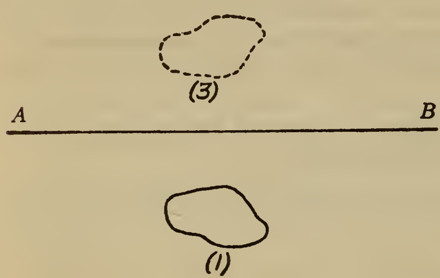

FIG. 39

The formula just derived can be used to find the resistance offered to flow of current either away from a single electrode buried in the earth, or from one electrode to another, these electrodes being of any shape whatever, if the value of C and the resistivity of the soil are known. Where a single electrode is concerned, refer to Fig. 39. Here A B is a plane passing through the medium described above, while (3) is the image of the electrode (1) above the plane. With (1) and (3) at the same potential, and current flowing away from both of them toward infinity, the electric field will be symmetrical with respect to the plane A B in accordance with the law of images. The resistance to current flow will be $R=\rho/4\pi$ C, since, as stated above, it makes no difference whether the electrode inclosed by S is composed of a single conductor or several separate conductors. Now, the electric fields being symmetrical, the half of the medium above the plane may be imagined to be removed without disturbing the field in the other half. The remainder may then be taken as representing the earth, the plane A B forming the surface, because for practical purposes it may be assumed that the earth is a semi-infinitely extended conducting medium. With the upper half of the medium removed the formula becomes $R=\rho/2\pi$ C, for the reason that the resistance is then twice as great as before, R referring to the resistance to flow of current away from (1), while C refers to the combined electrostatic capacity in free space of (1) and (3).

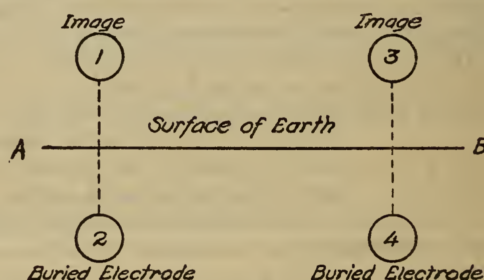

FIG. 40

Where two electrodes are concerned refer to Fig. 40. Here, A B is a plane passing through the medium as above, while (1) and (3) are the respective images of the electrodes (2) and (4) above the plane. With (1) and (2), and (3) and (4), respectively, at the same potential, and current flowing from (1) to (3) and also from (2) to (4), the electric field will be symmetrical with respect to A B. The resistance to flow of current will be $R = \rho / 4\pi C$. Now, as in the preceding paragraph, the half of the medium above A B may be imagined to be removed without disturbing the field in the other half, and the remainder taken as representing the earth. With the upper half of the medium removed the resistance becomes $R = \rho / 2\pi C$ as before, R referring to resistance to flow of current from (2) to (4) and C to the electrostatic capacity of the condenser formed by electrode (2) and its image (1), on the one hand, and electrode (4) and its image (3) on the other.

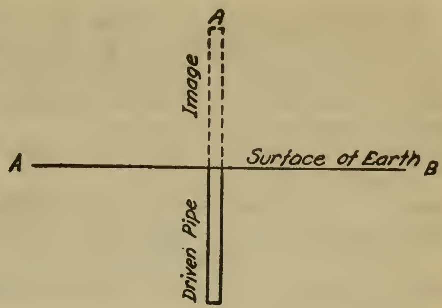

FIG. 41

To fix the ideas in regard to the capacity C, it may be considered that in Fig. 39 the capacity is that of (1) and (3) in free space when they are connected together by a fine wire, thus making a single conductor of them. In Fig. 40 the capacity is that between the conductors formed by connecting from (1) to (2) and from (3) to (4) with fine wires.

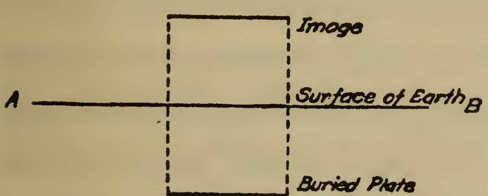

FIG. 42

The images in the cases of some of the forms of electrodes used in practice would be as follows: For a driven pipe, another pipe of the same size and length extending above the plane A B as in Fig. 41. For a plate, another plate of the same size situated in the same relative position above the plane A B, that the other is below as in Fig. 42.

In calculating C for the pipe the nearest approximation that can be made is that obtained by considering it an ellipsoid of revolution. The formula for the electrostatic capacity in free space of an ellipsoid of revolution of which the length of the major axis is great in comparison with that of the minor axis is $C = L/2 \log_e \frac{2L,}{d}$ where L is the length of the major axis and d of the minor axis. That is, L would be twice the length of the driven pipe and d its external diameter. There appear to be no available formulæ for other forms of electrodes.

With regard to ρ perhaps an explanation should be given of the use of this term which has been applied to soils in much the same sense as it is usually applied to metals. This application is not exactly rigorous because of the fact that the resistivity of soils is not as nearly continuous in the mathematical sense as is the resistivity of metals. That is to say, soil is made up of particles of insulating substances of various kinds such as quartz, mica, and the like, with the spaces between the particles filled to a greater or less extent with a water solution which is an electrolytic conductor. In passing from point to point in the earth, therefore, the resistivity may jump from very low values for points in the solution to extremely high values for points in the particles of mica and quartz. Hence, in speaking of the resistivity of the earth at a point the value actually meant is the average of that of a relatively large

volume in the vicinity of the point; and in speaking of earth of uniform resistivity it is meant that this average resistivity is uniform throughout the entire volume.

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